Numerical Simulation of Groundwater Depletion in Al-Hasa Area

by

Jamal Khaled Nejem

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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UMI Number: 1362011

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Ann Arbor, MI 48103

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بسم الله الرحمن الرحيم

إهداء

إلى الراحلَين بعيداً أبي وأمي ... يرحمهما الله ...

إلى إخوتي :

أبي خالد ... محمد

أبي جعفر ... عمر

أبي محمد ... أحمد

محمود (الحكيم)

أبي الحكم ... أشرف

وإلى أخَواتي ... مصدر الحنان ...

ثم إلى كل المخلصين المهتمين بموارد أمتنا ومصادرها ، حاثاً إياهم لمزيد من الاهتمام والإخلاص ، وداعياً لهم بالسؤدد والسداد .

ACKNOWLEDGEMENTS

Praise and gratitude be to **ALLAH**, Almighty, with whose gracious help it was possible to accomplish this work. Acknowledgement is due to King Fahd University of Petroleum and Minerals for extending the facilities to carry out this research.

I am indebted to my advisor Dr. Rasheed I. Allayla for his guidance and helpful suggestions throughout this study. Thanks are due to Dr. Taher Hussain (Co-advisor), Dr. Nasser Khondaker, and Dr. Achi M. Ishaq, my committee members, for their valuable suggestions and significant contributions.

Sincere appreciations should go to Dr. Ghazi Al-Sulaimani and Dr. Al-Farabi Sharif who lent a considerable help as chairmen of Civil Engineering Department. Acknowledgement is also due to my brothers Dr. Abdulla Al-Saeedi, Rajai Al-Assar, and Owais Peracha. Their limitless help accompanied me throughout. The things they did to make this work possible is over-emphasis. May ALLAH reward them in "Donya" and "AKherah".

My thanks must be extended to Dr. Yahya Al-Nabulsi from King Faisal University. Dr. Walid Abderrahman deserves great thanks for his support and encouragement throughout the thesis work. Also, I wish to thank brother Osama Abdelwahhab who devoted a lot of time to help me. Gratitudes are due to Dr. Hasan Al-Ahmadi and my eldest brother Ibrahim Aasi. Ibrahim's support was there till the last moment.

I wish to thank all brothers and colleagues at the university, especially Abdellmalik Abu-Shiekh, Nabil Abu-Zaid, Zakareyya Al-Hammouz, Iyaz Hasan, Mohammad Hussein Issa, Abdulsalam Mohammad and Shuaib Salman.

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خلاصة الرسالة

اسم الطالب الكامل : جمال خالد نجم

عنوان الرسالة : محاكاة عددية لهبوط المياه الجوفية في منطقة الإحساء

التخصص : هندسة مدنية (هندسة موارد المياه والبيئة)

تاريخ الشهادة : يونيو ١٩٩٤م .

تعاني واحة الإحساء من هبوط حاد ومستمر في مستويات المياه الجوفية : بلغ أوجهه في الخزانات الجوفية الرئيسة للواحة زاد عن ٣٠م في الهفوف وما جاورها .

لقد استُعمل في هذه الدراسة نموذج رقمي شبه ثلاثي الأبعاد لتمثيل ومحاكاة (نمذجة) المياه الجوفية في نظام متعدد الخزانات (خزانات النيوجين ، والخبر – العلاة) بالواحة . ولم تقتصر المساحة المدروسة على واحة الإحساء وحسب بل ضَمَّت جُزْءاً من المناطق المجاورة وذلك لاعتماد تدفّق المياه الجوفية على هذه المناطق . وتمت معايرة النموذج المستخدم باعتماد التدفق غير المنتظم للمياه الجوفية لأن الواحة بقيت في حالة ديناميكية متغيرة منذ مطالع السبعينات . وقد أكدت نتائج النمذجة وجود تفاعل هيدروليكي متبادل بين الخزانات المائية ، ومن ثم استخدم النموذج المعاير في توقع استجابة الخزانات لضخ المياه عبر فترة خمس سنوات (١٩٩٢ – ١٩٩٧م) ، وذلك من خلال اثنين من البدائل الممكنة لاستغلالها .

وقد أوضح النموذج في حالة عدم تغيير كميات الضخ الحالية (البديل الأول) فإن عام ١٩٩٦/١٩٩٧م سيشهد مزيداً من الهبوط في الجهة الجنوبية الوسطى من منطقة الدراسة . وفي حالة البديل الثاني (الترشيد والاقتصاد) لابد من استعمال المصادر غير التقليدية كمياه الصرف الصحي المعالجة للدرجة الثانية ، ومياه الصرف الزراعية التي لاتزيد نسبة الأملاح الكلية بها عن ٢٠٠٠ ملغم/لتر ، بالاضافة إلى مكننة البوابات والصمامات الخاصة بقنوات الري والصرف بمشروع الاحساء وربطها جميعاً بنظام تحكم حاسوبي . إن هذا الترشيد والاقتصاد في مياه الواحة سيوفر في أضعف الايمان ٢٩٪ بل ويمكن أن يصل إلى ٣٩٪ من كميات الضخ في الإحساء ، مما سيكون له طيب الأثر في ضمان إنتاجية أطول للخزانات المائية في الواحة.

درجة الماجستير

جامعة الملك فهد للبترول والمعادن

الظهران ، المملكة العربية السعودية

يونيو ١٩٩٤م

ABSTRACT

Name: **Jamal Khaled Nejem**

Title of Study: **Numerical Simulation of Groundwater Depletion in Al-Hasa Area**

Major Field: **Civil Engineering (Water Resources & Environmental)**

Date of Degree: **June 1994**

Al-Hasa Oasis is suffering from severe and continuous depletion in its groundwater. The water drawdown reached more than 30 meters at Al-Huffof and its vacinity.

In this study, a numerical quasi-three dimensional groundwater flow model was utilized for a multi-aquifer system in Al-Hasa (Neogene and Khobar-Alat Aquifers) to simulate the groundwater in the Oasis and, then, to evaluate the consequences of various development alternatives. The studied area consisted of the Oasis as well as some of the nearby regions because of the dependency of the groundwater on these areas. The groundwater in the Oasis has been in dynamic mode since 1970s. Thus, transient calibration was carried out. The model results have confirmed the hydraulic interaction between the aquifers. Subsequently, the calibrated model was used to forecast aquifers responses over a five-years period (1992-1997) under two development alternatives. With the first alternative of no-change in the present pumpage patterns, the model results indicated that more and more drawdowns will take place at a depletion rate of 5 meter/year. In addition, a cone of depression will occur in the southern middle part of the study area. The conservation option (Alternative II) requires the use of secondary traeted sewage effluent (that meets the standards of Food & Agriculture Organization) and the agricultural drainage water (of total dissolved solids < 2000 mg/L). Another part of conservation is the automation of Al-Hasa Irrigation and Drainage Project via computerized control of gates, valves, .. etc in all canals. These three conservation components will reduce the total extracted groundwater by 29% to 39%, which would ensure longer-term productivity of all aquifers in the Oasis.

MASTER OF SCIENCE DEGREE

King Fahd University of Petroleum and Minerals
Dhahran, Saudi Arabia

Chapter 1

INTRODUCTION

1. 1 General

Saudi Arabia will face a potential water crises in the early part of the next century (Temperley, 1992). It is the largest country in the world without perennial rivers, streams or fresh-water lakes because rainfall is both scare and sporadic and the evaporation rate is extremely high. The average annual precipitation is around 100 mm in the central and the eastern parts of the kingdom, while the loss through evaporation exceeds 3000 mm (Figure 1.1). So, the country virtually has no permanent sources of surface water except flash flood water in wadis of the western section and natural springs rising in the Eastern Coastal Zone (Figure 1.2).

Another reason for water crisis is the heavy reliance of almost all activities in the country on groundwater. The maintenance of existing Saudi agricultural production requires over eight billion cubic meters ($8 \times 10^9\ m^3$) of water per year. In addition, Urban, Rural and Industrial water requirements presently amount to over two billion cubic meters ($2 \times 10^9\ m^3$) of water per year. Should Saudi Arabia continue its development at the same current rate, its irrigation

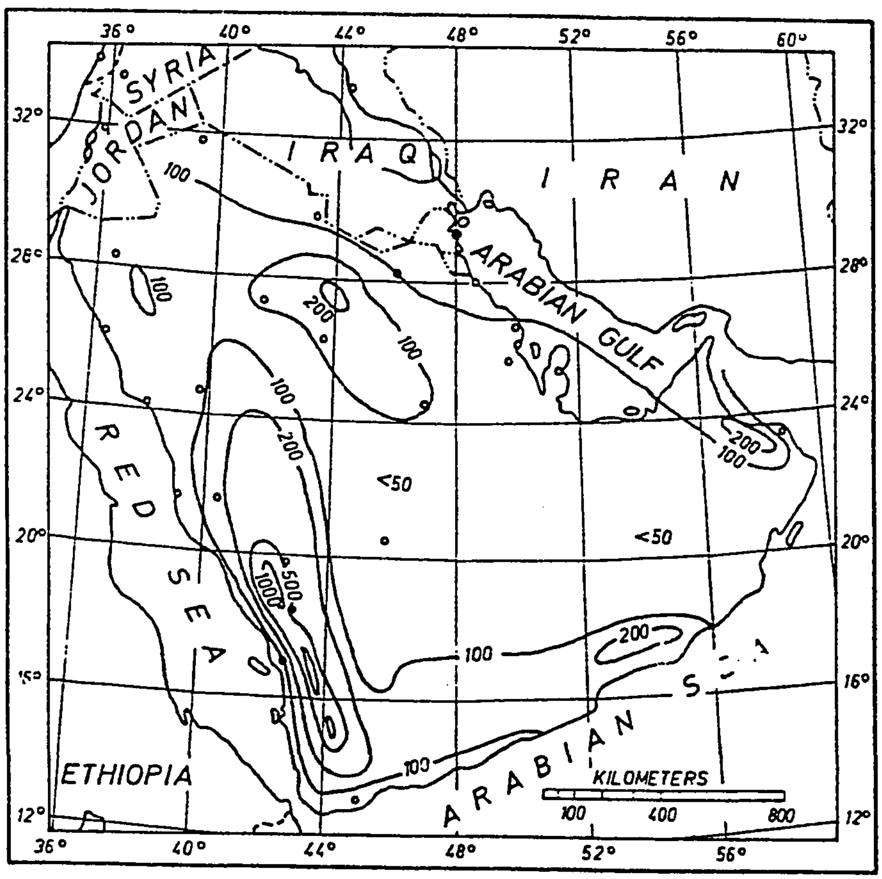


Figure 1.1 Isohyetes of the average yearly precipitation in millimeters. From A. BAUMGARTNER, E. REICHEL (1975), completed with data from ARAMCO (Dhahran) and the Ministry of Agriculture and Water (Ar Riyadh)

(After Al-Sayari & Zotl, 1978)

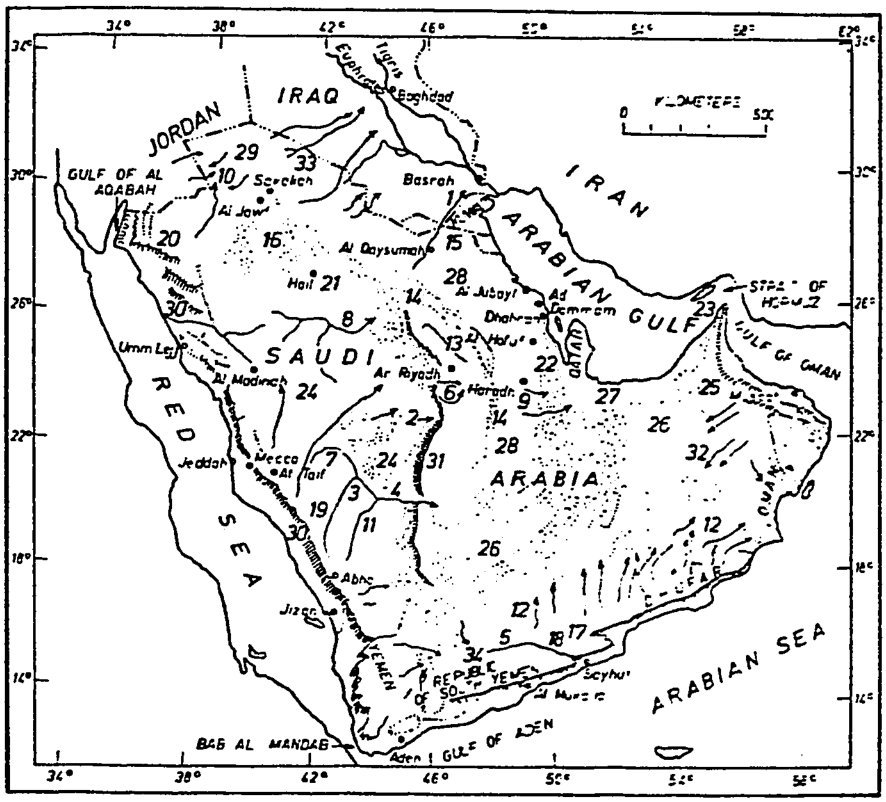


Figure 1.2 Map of the Arabian Peninsula showing the principal geomorphic features. Numbers indicate the locations of the wadis and landforms listed in the following explanation.

Wadis: *1* Wadi Al Batin, *2* Wadi Birk, *3* Wadi Bishah, *4* Wadi Ad Dawasir, *5* Wadi Hadhramawt, *6* Wadi Nisah, *7* Wadi Ranyah, *8* Wadi Ar Rimah, *9* Wadi As Sahba, *10* Wadi As Sirhan, *11* Wadi Tathlith

Land Forms: *12* Aden Hinterland, *13* Al 'Aramah Escarpment, *14* Ad Dahna, *15* Ad Dibdibah, *16* Great Nefud, *17* Hadhramawt Plateau, *18* Hadhramawt Valley, *19* Al Hijaz Plateau, *20* Hisma Plateau, *21* Jabal Shammar, *22* Al Jafurah, *23* Musandam Peninsula, *24* Najd Pediplain, *25* Oman Mountains, *26* Ar Rub' Al Khali, *27* Sabkhat Matti, *28* As Summan Plateau, *29* Syrian Plateau, *30* Tihamah, *31* Tuwayq Escarpment, *32* Umm As Samim, *33* Al Widyan, *34* Yemen Highlands

(After Al-Sayari & Zotl, 1978)

requirements by the year 2010 A.D. will be about eighteen billion cubic meters ($18 x 10^9 m^3$) of water per year. Over the same period, Urban, Rural and Industrial water requirements will go up to about three billion cubic meters ($3 x 10^9 m^3$) of water per year.

So far, Saudi Arabia has been using Fourteen major aquifers and thirteen minor ones. The major aquifers are : Al-Saq, Rawdh, Mazalij, Sharawrah, Tawil, Sakaka, Wajid, Minjur, Biyadh, Wasi'a, *Umm Er Radhuma, Khobar, Alat and Mio-Pliocene aquifers.* However, almost all groundwater supplies are alarmingly depleted due to the huge Agricultural, Urban, Rural and Industrial water requirements.

Such a great potential for groundwater was not known before 1930s. Early water demands were very much limited and were mainly met with wadi rain-flooding or with shallow, hand-dug water wells. The first deep water well in the Eastern Province was drilled in 1936 by the Arabian American Oil Company (ARAMCO) in its early stages of oil exploration. Since then, very rapid changes have been taking place in Saudi Arabia. Such overturns were accompanied with the construction of new industries, the employment of huge numbers of foreign manpower, the cultivation of much greater lands than ever before and other developments which necessitated a continuous need for new water resources (El-Naggar, 1986). This is particularly of great concern in Al-Hasa Area , in the Eastern Province where the first oil well was drilled.

1. 2 Statement of the Problem

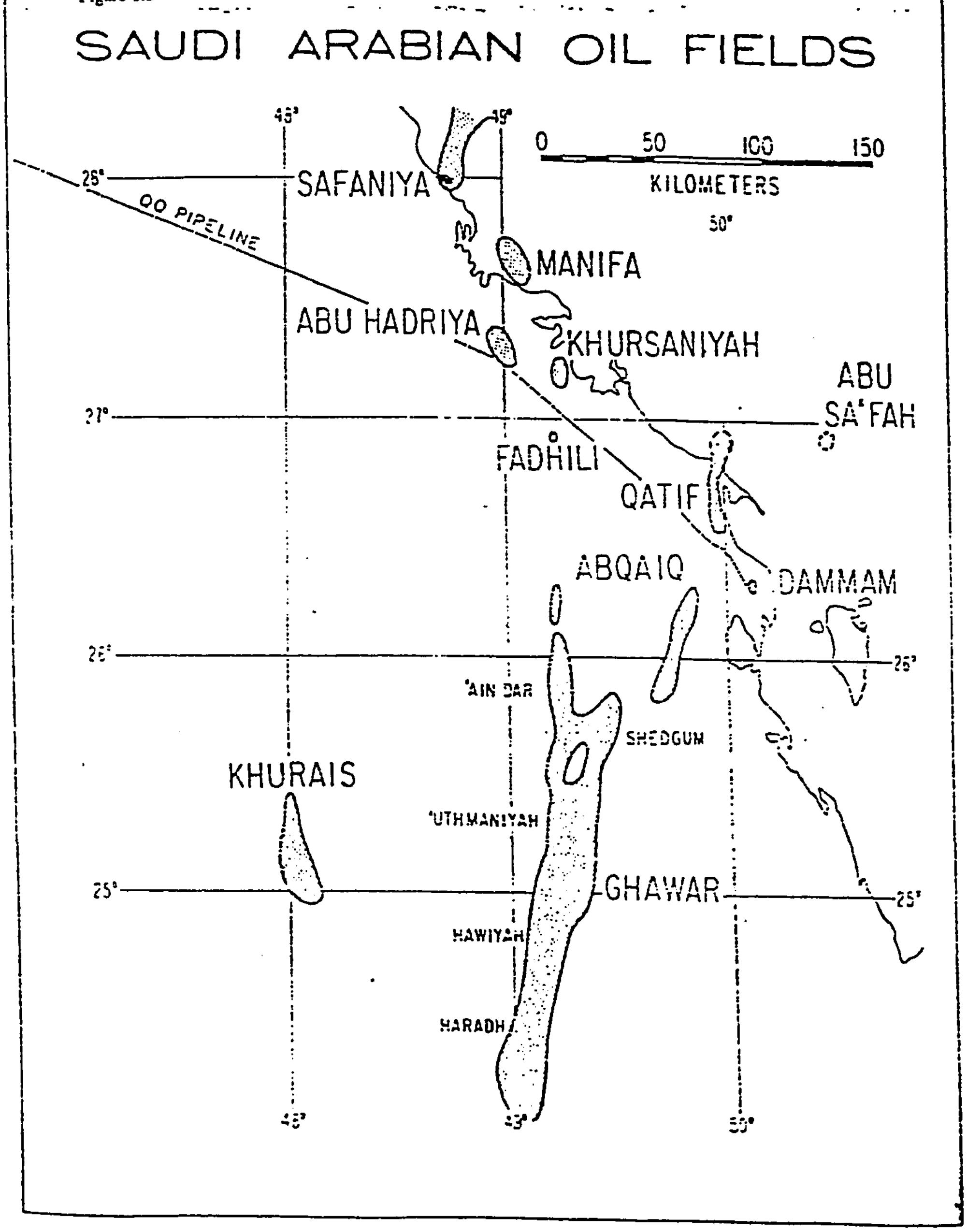
Al-Hasa used to have a large number of artesian springs. For hundreds of years, those springs have been a reliable source of water for irrigation. The plenitude of water, together with the availability of both labor and arable land, made the Oasis one of the most intensively cultivated regions in Arabia and gave it its economic stability (Humaidan, 1980). For decades, Al-Hasa offered abundant amounts of agricultural products to other parts in the country and neighboring states.

Prior to 1960s, the intensive cultivated area in Al-Hasa was about 20,000 hectares. Unfortunately, excessive irrigation, poor drainage - among other factors- forced the available arable lands to shrink to about 8,000 hectares at the end of 1963 (Wakuti-Consulting Engineers, 1964).

The discovery of oil in the Eastern Province has accelerated all sorts of developments in the region, especially at Al-Hasa. Actually, the biggest oil field in Saudi Arabia (Al-Ghawar Field) was found very close to Al-Hasa (Figure 1.3). In 1971, *Al-Hasa Irrigation and Drainage Improvement Project* was completed and officially inaugurated. The project's primary objectives were :

1. Setting up a rational and efficient irrigation system that serves the irrigated areas better, reduces losses, and

Figure 1.3



(After Naimi, 1965)

ensures more rational use of wells and springs in Al-Hasa

2. Constructing an effective drainage system which would prevent water logging that occurred in various parts, and facilitate the removal of harmful salts from the soil

3. Reviving an area of 12,000 hectares in addition to the existing 8,000 hectares, returning the total cultivated land to its original area of 20,000 (Wakuti-Consulting Engineers, 1971).

Al-Hasa Irrigation and Drainage Improvement Project consisted of two major parts : an *irrigation system* and a *conjugate drainage* one. The new system of irrigation canals is about 1,500 kilometers long while the drainage networks extends to about 1,600 kilometers. The irrigation network system was constructed of main canals (155 kilometers), sub-canals (265 kilometers), lateral canals (1,100 kilometers), three elevated reservoirs and three pumping stations (El-Khatib, 1974). The reinforced concrete network combines and redistributes water from 32 main springs in the Oasis. The complementary drainage network has more than 1,300 kilometers of lateral, sub-, and main canals that lead drainage water to evaporation lakes outside the Oasis.

Since 1967, drilling of wells has been prohibited within the Oasis area that is covered by the new irrigation and drainage system. The only areas where drilling is allowed are the southern part of the Oasis and areas where the new irrigation waters cannot feed them (Leichtweiss-Team, 1979). In the last 20 years, the number of wells has increased rapidly due to a new act allowing farmers to dig wells, which resulted in severe drop of groundwater levels throughout the whole Oasis (Al-Taher, 1987).

Some advantages have been attained by Al-Hasa Irrigation and Drainage Improvement Project. But, the project has fallen short in achieving its goal of putting 20,000 hectares under cultivation (Humaidan, 1980). In addition to that, the existing water management practices have detrimental effects on the Oasis groundwater.

A hydrogeological study indicated that the total balanced production of groundwater within Al-Hasa without affecting the artesian flow was about 10.13 m^3/s (BRGM, 1977). The total groundwater withdrawal in 1990 was about 13.45 m^3/s and in 1995 it is expected to exceed 19.96 m^3/s. Taking the flow of 10.13 m^3/s as the base value for calculation, these withdrawals are, respectively, about 32.8 and 97.04 per cent (32.8 % and 97.04 % respectively) above the estimated production rate of 10.13 m^3/s. A pumping rate increase of 20 per cent was established to be the critical threshold limit above which almost all springs in the Oasis will cease its artesian flow after 1987 (Abderrahman and Ukayli, 1984). Obviously, the above mentioned increases in pumpage exceeded that limit to a pronounced level. Should the current rate of Al-Hasa large agricultural, social and other activities continue at the same rate, the growing water demand for all purposes (especially for irrigation) will rise to some billions of cubic meters of water per year- which exceeds all balanced groundwater supplies in the region (Temperley, 1992).

The intensive developments of Al-Hasa Oasis agriculture over the last twenty years is now taking its toll. Official- yet unpublished- reports consider that a major problem is now developing in regard to *depletion* of the Oasis groundwater reserves. Currently, some 90 per cent of the irrigation water used through Al-Hasa originates in deep groundwaters, "Fossil Water". As a result of excessive draw-off, the aquifers holding these waters, almost all, demonstrate considerable reduction in both static water levels (SWL) and quality. Unfortunately- and from hydrogeological viewpoint- old and deep aquifers may take hundreds, even thousands of years to replenish.

1. 3 Research Objectives

The deep groundwaters of Al-Hasa are clearly non-renewable resources. Such a depleting asset *should not* be squandered needlessly, but should be conserved wherever possible for the use of future generations. The water levels in the various aquifers must be maintained to retain the present level of natural fertility in the Oasis. Otherwise, subsequent reduction in the water table level will adversely affect agricultural developments in the area. Because once fertile, farms and small holdings might start reverting into arid desert through removal of the topsoil by the prevailing winds . Furthermore, progressive fall of water levels could result in an irreversible *collapse (subsidence)* of the aquifers pores themselves. If such a disaster happened, then the geological bearing formations that have been created 400 centuries ago would be lost in a couple of years (Temperley, 1992).

Thus, there exists a growing need for comprehensive studies in order to have a better understanding of the causes of groundwater depletion in the area. Numerical models are the most powerful and extensively used engineering tools for the investigation of the effects of the identified factors on the groundwater level fluctuation. They are also helpful in selecting appropriate remedial measures to control various problems related to groundwater depletion.

This research is initiated to achieve the following objectives:

1. Simulation of the transient groundwater flow behavior at Al-Hasa using a suitable Computational Model

2. Investigation of the effects of identified cause(s) on the groundwater depletion under various scenarios by numerical experiments

3. Recommendation of feasible remedial measures to control the existing depletion.

Chapter 2

LITERATURE REVIEW

2. 1 Brief Literature Survey

The most relevant works regarding groundwater in Eastern Province began in 1965 and thereafter. Initial hydrogeological studies were very general and not concerned directly with Al-Hasa area. The following is a scan of the most relevant works regarding Al-Hasa water resources, especially groundwater.

Wakuti- a Swiss consulting firm- made detailed field investigations, recommendations and designs for what is known later as "AL-Hasa Irrigation and Drainage Improvement Project". They studied various water resources and agricultural engineering aspects regarding the project (Wakuti-Consulting Engineers, 1964). Over the five-year period of 1967-1971, Wakuti was sponsored by the Saudi Arabian Ministry of Agriculture and Water to supervise the construction stage of the same project.

In his report, Naimi (1965) provided general maps for water levels and salinities of various aquifers in the Eastern Province of Saudi Arabia. He, also, gave an idea about the general productivity of various hydrological units in Al-Hasa Oasis and other areas of the province. Furthermore, The study has supplied data on water quality and hydraulic gradient values.

Italconsult (1966-69) started a four-year study of area IV (the eastern province of Saudi Arabia) for the Ministry of Agriculture and Water (MAW). They provided a detailed investigation of the hydrogeology of the Eastern Province. Their study, also, highlighted a comprehensive understanding of the regional hydrogeology of different aquifers in the region investigated.

In 1973, the Leichtweiss-Institute for Water Research of the Technical University of Braunschweig/ West Germany, installed a new measurement system at various springs and in the main irrigation canals. The first results are given in the report "Water Measurement in the Al-Hasa Oasis 1973". Between 1974 and 1978, an integrated research program of Leichtweiss-Team at Al-Hofuf Agricultural Research Centre (HARC) resulted in a series of publications regarding water resources of Al-Hasa Oasis, hydrogeological and soil investigations, and irrigation guidelines for the Oasis - to mention only few publications.

Under another contract for the Ministry of Agriculture and Water in 1977, the Bureau de Recherches Geologique et Minieres (BRGM) investigated the geology and hydrogeology of Al-Hasa Oasis. The primary objectives the BRGM-Study were to estimate water quantity in Wasia-Biyadh sequence, and to measure withdrawal effects on Umm Er Radhuma (UER), Khobar-Alat and Neogene aquifers. Also, they constructed a quasi-three dimensional flow model to simulate the multi-aquifer system in the region. Their model was on a regional scale with a grid spacing of 10 by 10 kilometers. BRGM-Study utilized their results as the main tool to interpret the anomalies in the hydrogeological maps. In addition to that, the study has provided information about transmissivities, storage coefficients and vertical leakances in the region.

Humaidan (1980), developed policies and management guidelines to give resource utilization results near to an economic optimum for Al-Hasa Irrigation and Drainage Project. According to him, such policies should be based on the premise that irrigation water from Al-Hasa springs is a scarce resource. Having this in mind, Humaidan concluded that such valuable limited resource should be allocated among crops and cropping patterns so as to maximize long-run net returns for the Oasis.

In 1980, the Groundwater Development Consultants (GDC, 1980) carried out a regional study on the Umm Er Radhuma aquifer. The study provided some data on the hydrodynamics and the abstraction rates of Umm Er Radhuma, Khobar-Alat, and Neogene aquifers. The GDC developed a multi-aquifer simulation model of the previous aquifers interconnected through Rus aquitard. Mainly, the GDC study focussed on Bahrain island. And, the model utilized large grid spacing.

Job (1978), Beckman and Ramsay (1978), Moser et. al. (1978) and Abderrahman (1982) carried out some researches on the water chemical quality of Neogene aquifer at Al-Hasa.

Bakiewicz et. al. (1982) examined the hydrogeology of Umm er Radhuma aquifer with reference to fossil gradients. They attempted to resolve the problem of the origin of the observed groundwater gradients using analytical and numerical models. With the aid of the same models, they tried to discover the extent to which the past must influence present day plans for future development.

Abderrahman and Ukayli (1984) reviewed production and water level histories of Al-Hasa major springs in a strategic plan for water use in Al-Hasa Oasis. They have suggested a water supply plan for Al-Hasa Oasis. The plan suggested that the growing water demand in the Oasis in the next 20 years (1984-2004) can be met without further disturbance to the Al-Hasa groundwater by reusing sewage effluents and agricultural drainage water and utilizing additional groundwater resources from outside Al-Hasa.

Yazicigil et al. (1987), Allayla et al. (1987) and De Jong et al. (1987) conducted a comprehensive study for the optimal development of groundwater resources in the Eastern Province. They have combined Alat and Khobar aquifers in one single aquifer and developed three models : a two-dimensional simulation model, a solute transport model and an optimization model. Their model was on a regional scale with grid spacing of 10 by 10 kilometers.

In his M.S Thesis, Al-Mahmoud (1987) interpreted the hydrogeological conditions of some of the developed aquifers at Al-Hasa Oasis. He, Also, investigated the relations of these conditions to the geological structure of the area. Furthermore, Al-Mahmoud investigated the chemical quality of water in the aquifers and its suitability for different uses.

Al-Taher (1987) completed his Ph.D Dissertation under the title : "Irrigation Efficiency and Production Energy Efficiency of Traditional and Modern Farms in the Al-Hassa Oasis, Saudi Arabia". The primary purposes of his study were to determine the irrigation efficiency of all irrigation methods used in the Oasis, to assess the production energy flow for representative operations, and to relate the food energy output to energy demands of crop production - to mention some of his research objectives.

Rasheeduddin (1988) studied Alat, Khobar, and Umm Er Radhuma aquifers numerically. He used a three dimensional finite difference groundwater flow model (developed by McDonald and Harbaugh 1984). He assumed a "quasi"-three dimensional case, and considered Alat, Khobar and Umm Er Radhuma as a multi-aquifer system. Rasheeduddin, also, predicted responses of the aquifers over a planning horizon of 14 years (1987 - 2000) under three development alternatives.

Al-Assar (1992) used three-dimensional finite difference groundwater flow model developed by McDonald and Harbaugh (1984). He simulated the groundwater of Umm Er Radhuma aquifer in two dimensions in the project area of Al-Sharqia Agricultural & Development

Company (SHADCO). He utilized a block-centered grid that covered the 90 square kilometers project area. Al-Assar simulated 75 deep wells within the project region that are drilled in the Umm Er Radhuma aquifer. He predicted the aquifer responses for a 7-year planning period, where different management alternatives and schemes were evaluated.

2. 2 Present State of the Problem

As mentioned earlier, the Kingdom of Saudi Arabia does not have an abundance of water resources. It has no permanent surface water. It is severely aridic with very little rain and very high evaporation rates (Al-Mahmoud, 1987).

During the past fifteen years, the Kingdom, in general, and Eastern Province, in particular, have experienced rapid development in Agricultural, Urban, Rural, and Industrial fields. These developments were associated with increased reliance on available aquifers to satisfy the present and future demands. This has resulted in a dramatic groundwater depletion (Yazicigil et al., 1986). At the same time, salinities and water quality have deteriorated to a noticeable degree (Allayla et al. 1986 and De Jong et al. 1986).

Saudi Arabia *wheat production* was 3.2×10^6 , 3.6×10^6 and over 4×10^6 tons in 1989, 1990 and 1991 respectively while *wheat exports* were about 2×10^6 tons in 1991. This is well in excess of in-country needs. Saudi Arabia is also self sufficient in dates and eggs. If the present development rate is to maintain, the country irrigation requirement will be over $10.9 \, x \, 10^9$ gallons per day (gpd) by the year 2010 A.D. Over the same period, it is estimated that some $1.8 \, x \, 10^9$ gallons per day (gpd) are to be supplied for Urban, Rural and Industrial purposes.

The literature review of the previous section showed that there were no problems regarding groundwater withdrawal and depletion. Studies of Naimi (1965), Italconsult (1969), and Al-Mahmoud (1987) were general and concerned, mainly, with investigating the geological, hydrological and hydrogeological aspects of the aquifers in the region.

In 1977, and thereafter, the Ministry of Agriculture and Water employed different specialized agencies to give more detailed and comprehensive studies of the hydrogeological condition in the Eastern Province. BRGM (1977) and GDC (1980) constructed simulation models that brought up very useful results. Those results were utilized by other researchers, later on, as inputs to other constructed or developed simulation models (Yazicigil et al. 1987). Some of the models were of regional scale and appropriate grid spacing. Other models used large grid spacing and concentrated on specific regions (like that of GDC (1980) which focussed on Bahrain Island).

All recent studies indicate that the water level in various aquifers is falling down at unprecedented rate. Concurrently, salinities and water quality have deteriorated to a pronounced degree. In fact, U.S.A. authorities have suggested that critical aquifer levels will be approached in the coming ten years, unless alternative sources of water are developed and water policy is reversed (Temperley, 1992).

Al-Hasa, the largest and the oldest oasis in the Arabian Peninsula, is the biggest example for the groundwater depletion problem. The main occupation in the Oasis is agriculture. Although there are no official figures on the total number of people presently working in agriculture, many knowledgeable experts are of the opinion that the number of those who are involved in agriculture is at least 500,000. This is about 62 % (62 per cent) of the total Al-Hasa inhabitants (Abderrahman and Ukayli, 1984). Agriculture, in Al-Hasa, is of paramount importance to the Oasis economy both in terms of farmer number and income generated.

During 1960s, Saudi Arabian Ministry of Agriculture and Water embarked Al-Hasa Irrigation and Drainage Improvement Project (HIDIP). The main objective of the project was to extend the existing 8,000 hectares farm lands to a total of 20,000 hectares.

Since 1971, the time by which the project has been in full operation, millions of cubic meters of groundwater were squandered without achieving the anticipated goal of putting 20,000 hectares under cultivation (Humaidan, 1980). Al-Hasa Irrigation and Drainage Authority (HIDA), who operates and manages the project, pumped about 240 million cubic meters ($2.4 \times 10^8\ m^3$) per year for the period of 1974-1978. More or less amounts of groundwater were pumped thereafter. To see how much the waste in the extracted water was, it is enough to point out that official records for the same period (period of 1974-1977) showed that the average volume of water flowing in the drainage system was 52 per cent (52 %) of the volume distributed for irrigation.

2. 3 Justification of the Proposed Research

Groundwater is the primary limiting factor in the expansion of the irrigated area in Al-Hasa. The improper guidance and restraints in the suitable use and conservation of this scarce wealth has confined the total cropped area to a magnitude much less than the expected potential of the Al-Hasa Irrigation and Drainage Improvement Project (Humaidan, 1980). If available water were more efficiently utilized, it is believed that more land could be brought under cultivation, higher net returns per water-unit could be forthcoming, and - definitely more important - huge groundwater quantities could have been saved for future.

The alarming depletion in groundwater levels, and the potential threat of a severe water crisis in the region demands continuous efforts in the development of computer-based methodology. This methodology is to be used for mathematical analysis of the mechanisms of groundwater systems, controls of groundwater related problems, and for the evaluation of actual and/or proposed human-induced changes in the system.

The present study is aimed to make use of the previous efforts, and to utilize a three-dimensional simulation model for local groundwater condition in Al-Hasa. The study is also aimed to enhance a thorough understanding of the prevailing hydrogeological condition and the results of continued withdrawals of Al-Hasa aquifer system. It is expected to generate possible alternatives that may help better utilization of the groundwater resources and possible remedial measures to control the groundwater depletion in the study area.

The outcome of the proposed research is expected to be of great importance to all those who are using Al-Hasa groundwater. The study results would, also, help in the development of efficient and cost-effective policy to conserve the depleted aquifers in the Al-Hasa Oasis. The present work could form a research model to other areas in the Kingdom where groundwater aquifers are facing (or will face, as expected) severe depletion problems. This is particularly applicable to Tabouk and Al-Kharj regions.

Chapter 3

DESCRIPTION OF THE STUDY AREA

3. 1 Introduction

3. 1. 1 Historical Perspective

Al-Hasa Oasis is probably one of the oldest existing agricultural world centers. Twenty centuries ago, Strabo in his "Geography of the Roman Empire", reported the existence of a river originating in Al-Hasa and flowing to Al-Uqayr, an ancient port on the Arabian Gulf. At old days, the Oasis used to be a hosting place for merchants crossing the area between the Mediterranean and India (BRGM, 1977). A number of scholars of different nationalities and backgrounds travelled through Al-Hasa. They wrote very informative accounts about the Oasis. Ibn Battutah (1854), Zwemer (1900), and Lorimer (1908) are among those scholarly men. All were in agreement on the fact that Al-Hasa was an important economic center both as agricultural production area and as a trading region (Humaidan, 1980).

3. 1. 2 Geographical Perspective

The Oasis forms the central part of what is known historically as *"AL-AHsa' Region"*. Al-AHsa' used to be the *old* eastern province of Saudi Arabia with boundaries running from Kuwait Neutral Zone in the north to Ar Ruba' Al-Khali (Empty Quarter) in the south, and from the Arabian Gulf in the east to Ad Dahna desert in the west. That area encompasses 41,200 square miles, the capital of which was Al-Hofuf (Britannica Encyclopedia, 1973).

Nowadays, Al-Hasa Oasis is a part of the Eastern Province of Saudi Arabia. Al-Hofuf has ceased to be the provincial capital, which is now Ad Dammam. The recent borders of the Oasis covers a total area of about $600\,km^2$ (six hundreds square kilometers) which is equivalent to 60,000 hectares or 600,000 dunums that takes, roughly, an "L" shape with the vertical stroke of "L" lying in a north-south direction and consisting the longest axis. It lies $50\,km$ (fifty kilometers) to the west of the Arabian Gulf cost. The Oasis expands from latitude 25° 18' 03" N to latitude 25° 38' 12" N and from longitude 49° 32' 21" E to longitude 49° 47' 09" E (Figure 3.1). The study area was extended to include parts of other areas like Shedgum, Uthmaniyah and Al-Ghwaibah (Figure 3.2), because of the dependency of the groundwater conditions in the Oasis on the nearby areas.

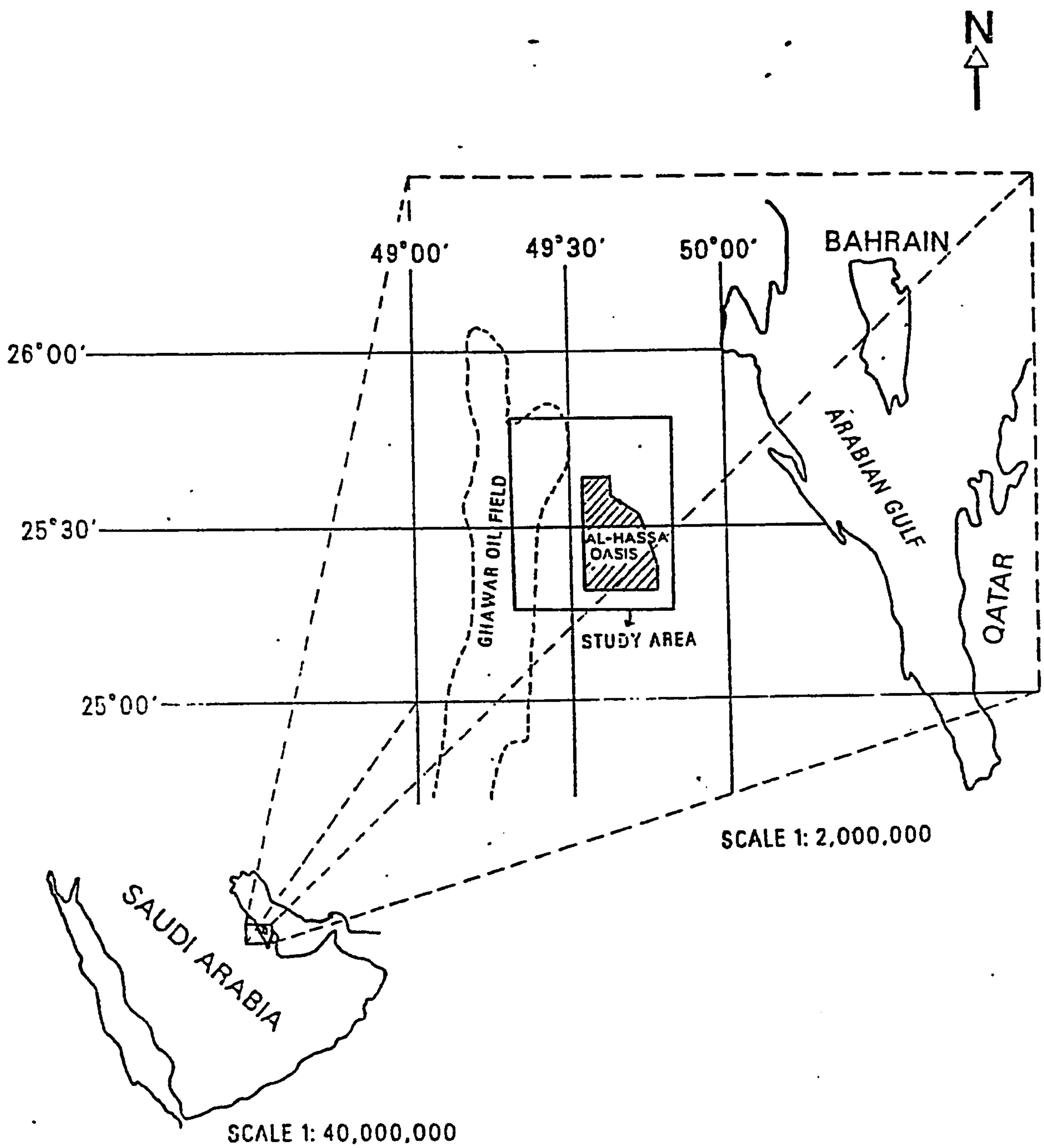


Figure 3.1 Location Map of The Study Area

(After Al-Mahmoud, 1987)

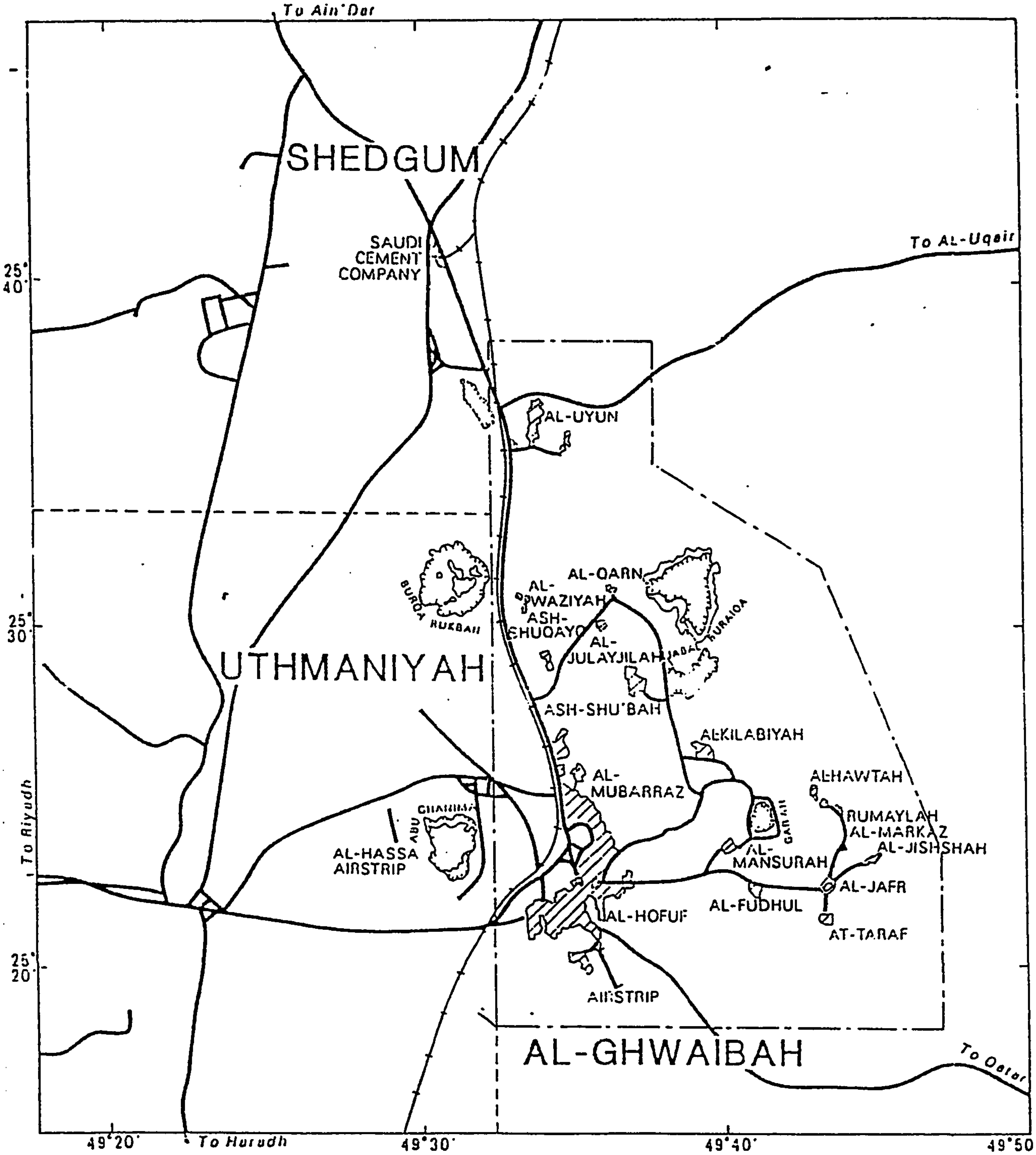


Figure 3.2 Map Showing the Areas Adjacent to Al-Hasa Oasis (After Al-Mahmoud, 1987)

3 0 3 6 9 12

KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- TOWN OR VILLAGE
- JABAL

The last population's estimate showed that Al-Hasa had a total population of about 535,000 (Al-Mahmoud, 1987). The present population number is believed to be around 812,000 (Abderrahman and Ukayli, 1984), most of whom are congregated in the three major cities of Al-Hofuf, Al-Mubarraz and Al-Uyun. Remaining inhabitants are distributed between about 48 villages within the Oasis domain.

Some of Al-Hasa population work in non-agricultural sectors, particularly in oil industry. However, agriculture is still, and will probably continue to be, the main occupation for most of the people there.

3. 2 Geology of the Study Area

Al-Hasa Oasis is about 130 to 160 meters above the sea level. The plain between the Oasis and the coast, sloping with a very low gradient towards the east, is covered by sand dunes of Al-Jafurah and is partly dikakah. To the west, Shedgum Plateau rises to an altitude of 290 meters.

Al-Hasa is one of the largest oases in the world. Situated between the sand dunes covering the adjoining plain in the east and the rock desert of As-Summan Plateau in the west, the Oasis owes its existence to large karst springs at the eastern scrap of As-Summan Plateau.

Geologically a part of the Arabian Shelf, the Mesozoic and Cenozoic series of strata dip slightly towards the east. In the area of

Al-Hasa the outcrops consist only of Tertiary and Quaternary sedimentary rocks. The morphogeny and hydrogeology of this area is strongly influenced by the Ghawar structure laid out by Cretaceous and lower Tertiary tectonics. This north-south-trending anticline west of Al-Hasa is 20 to 40 kilometers wide (Hotzl and Zotl, 1978).

The field studies carried in the period (1973-1975) provide a basis to investigate the geology of the Oasis since the Pliocene. The following discussion is based on studies of D. A. Holm (1965), R. W. Powers et al. (1966), and R. W. Chapman (1971, 1974). Those studies help in the interpretation of various hydrological and hydrogeological aspects of Al-Hasa water-bearing formations.

3. 2. 1 Terrestrial Sedimentation of the Lower Pliocene

As Summan Plateau between Abqaiq and Haradh is a sedimentary complex of Miocene and Pliocene strata (R. W. Powers et al., 1966). The upper layers of this complex are exposed in the scrap towards near Al-Hasa. The Hofuf Formation, which is the upper series of strata, is composed of terrestrial sediments with almost no fossils. They lie on the marine strata of the Dam Formation, limestones, marls, and clays of the middle Miocene.

In the area of Al-Hofuf, a thin layer of marl is overlain by conglomerates to 17 meters thickness. The gravels of this stratum were transported under humid climatic conditions by rivers and are a product of fluviatile sedimentation. The humid period was followed by the deposition of sandy limestone to a thickness of 18 meters (Hotzl et al., 1978).

3. 2. 2 Pliocene-Pleistocene Marine Transgression and Regression

Marine transgression from the east took place during the Middle and Upper Pliocene. The consequence thereof was the erosion of parts of the terrestrial sediments of the Upper Miocene and lower Pliocene and the creation of the steep cliff of the recent eastern boundary of As Summan Plateau.

In Al-Hasa area, the cliff and its morphology are well developed. At the eastern border of As Summan Plateau, the top plain of Shedgum Plateau ranges from 270 to 280 meters above sea level. The abrasion plain in the front of the cliff exposes gray marls. The cliff was dissected and transformed by the runoff from the plateau beginning with the last phases of the marine regression (Hotzl et al., 1978).

3. 2. 3 Breakers Terraces and Caves of Jabal Al-Qarah

Jabal Al-Qarah is about 7 kilometers east of Al-Hofuf. It is a completely isolated remnant in front of the cliff of As Summan Plateau. It tops 205.5 meters above sea level (some 70 meters higher than the surrounding Oasis). The jabal covers an area of 1.7 square kilometers. It is consisted of marl and marly sandstone of the Hofuf Formation. Within the sandstone, layers of silt and clay are interbedded. The base of the jabal consists of grey marls.

At the western side of Jabal Al-Qarah, the ruptures meet the cliff at an acute angle. Here, the cliff face is strongly influenced by marine abrasion and lithological changes of strata. Depending on bed alternation, wave plantation and breakers exerted a sound influence (Hotzl et al., 1978). Sea caves, beside hollows, were developed extending more than 10 meters into the jabal.

At present, there is a maze-like cave system directly behind a threshing floor flooded - in parts- by runoffs from the western side of the jabal. The cave was later modified by fluviatile erosion as is reflected by young runoff channels. In addition to that, salt weathering was especially pronounced in clayey sandstone ((Hotzl et al., 1978), (Maurin et al., 1978), (Zotl et al., 1978)).

Infiltrated precipitation, time breakers and tides influenced the development of the cave system. The plateau at the top of Jabal Al-Qarah exhibits a dendritic drainage pattern. Some of the surface channels have depths of 4 meters and beds of few meters width. All recent surface runoff disappears into shafts.

Salt weathering plays an important role in the widening of the cave's cross-section. Mainly, it works on the fine clastic layers in the lower parts of the cave system. For this type of weathering the low permeability of the marly and clayey materials is to be taken into consideration (Hotzl et al., 1978).

Hotzl et al. (1978), Maurin et al. (1978), and Zotl et al. (1978) discussed the problem of existing waterways reaching below the surrounding land surface. As per them, the strata at the orographic base of Jabal Al-Qarah are partially permeable. Heavy rain floods reach the innerpart of certain caves only. Consequently, seepage occurs in spite of marly and clayey strata through north-northwest system of joints. Infiltration possibilities are of cardinal interest when the recent recharge amount of springs and groundwater in Al-Hasa Oasis is considered. Along the eastern edge of Shedgum Plateau, water-bearing shafts without any connection to caves in the cliffs were detected. Likewise, the surface of Barqa Ar Rukban, about 17 kilometers north-northwest of Al-Hofuf, has an open vertical shaft where the surface runoff of a depression disappears after a heavy rain. With such observations, it is not unusual to assume that As Summan Plateau belongs partly to the recharge area for the component of younger waters which get mixed with old waters discharging from deeper aquifers.

3. 2. 4 The Pliocene/ Pleistocene Delta of Wadi As Sah'ba

An enormous gravel fan, south of Al-Hasa Oasis, covers the plain between As Summan plateau and the coastal area from Salwah to Sabkhat Matti. The beginning of the fan is the cross channel of Wadi

As Sah'ba through As Summan Plateau near Haradh. The fan take an arch-shape that ranges from Al-Hofuf, in the north, to southwestern part near Qatar down to Ar Ruba' Al-Khali, in the south. The radius of this arch is more than 150 kilometers. The geometric form of this gravel fan is a flat semi-cone with an apex of 300 meters above sea level near Haradh.

Certain evidences made D. A. Holm (1960) and Powers et al. (1966) to conclude that the fan is deltaic. Topographically, gravel trains can be found over a distance of 50 kilometers or more. The channels within the delta of Wadi As Sah'ba are filled up with pebbles and coarse gravels. Between the channels, sand, small gravel lenses, and silt can be noticed.

3. 2. 5 Quaternary Erosion and Sedimentation

Al-Hasa topography has probably not changed much since the Plio-Pleistocene. Features like the cliff and its outliers, the plain towards the Gulf and the delta of Wadi As Sah'ba basically established in the Upper Pliocene. The Quaternary chiefly produced an erosive wind activity as well as eolian transport and its ensuing accumulation. It was the following huge sand transportation from the northwest, the main wind direction, which covered nearly the whole area with the transverse dunes of Al-Jafurah.

The narrow short gullies are witnesses of fluviatile erosion of the

Quaternary. The development of the recent channel of Wadi As Sah'ba is not clear. Numerous water well drillings show that the bottom of the wadi channel can be found at a depth of 30 meters (at 240 meters above sea level). The channel is filled with fine gravels, sand, marly limestone, gypsum and various salt crusts up to the recent wadi floor.

The Quaternary sediments in Al-Hofuf area are of various nature. Those sediments include sand and fine-grained material from the surface runoff, freshwater limestone, clayey marl, and sabkhah plains. The dunes have temporarily dammed up the runoff from the enormous karstwater springs, thus creating freshwater lakes and swamps. Different gastropods were established in the course of constructing the drainage channel northeast of Al-Hawtah.

East of Al-Hasa, silt, clay and salty clay were deposited in large sabkhahs. From These subkhahs, it can be concluded that the oasis must have had its drainage towards the Gulf until recently. Two drainage patterns have to be distinguished : the northern one coming from the area of Al Muhtaraqah-Al Qarn, and the other from the southern area of Al Qarah-At Taraf. Both of the previous patterns are running parallel towards the northeast ((Hotzl et al., 1978), (Maurin et al., 1978), (Zotl et al., 1978)).

Large dune areas have interrupted the surface runoff recently. However, in the Al-Uqayr area a surface runoff exists from the local coastal sabkhah. Hotzl et al. (1978), Maurin et al. (1978), and Zotl et al. (1978) assumed that this surface runoff is fed by the underground seepage from the evaporation pans of Al-Hasa. This assumption is conformed by the fact that this runoff in Al-Uqayr area has increased since the construction of the irrigation system in Al-Hasa.

3. 3 Review of Available Information

The data used in this thesis were abstracted from the published and unpublished material of the Saudi Arabian Ministry of Agriculture and Water. The material includes reports of various consulting firms, groundwater resources studies, and research progress reports. Additional information was based on published and unpublished reports of Hofuf Agricultural Research Center (HARC), Al-Hasa Irrigation and Drainage Authority (HIDA), Water Studies and Research Center - King Faisal University at Al-Hasa, and the Arabian American Oil Company (ARAMCO). A brief review of available information is presented in the following subsections.

3. 3. 1 Water Resources

In spite of the fact that Al-Hasa yearly rainfall averages less than 100 mm, abundant supplies of water were available from the three main underlying aquifers : *Umm er Radhuma, Dammam group, and the Neogene.* A generalized lithostratigraphic sequence of the study area is given in Table (3.1).

Table 3.1 Lithostratigraphic Sequence of the Water Bearing Foramtions at Al-Hasa Area
(Modified After Powers et. al, 1966)

AGE		FORMATION	MEMBER	GENERALIZED LITHOLOGIC DESCRIPTION	RANGE OF THICKNESS	HYDROGEOLOGY
Quaternary		Surficial deposits		Gravel, sand and silt	Generally less than 30 m.	Variable productivity, depending on recharge.
Tertiary	Neogene	Hofuf		Sandy marl and sandy limestone	0-95 m.	Generally called Neogene Aquifer.
		Dam		Marl and shale; subordinate sandstone; limestone	0-125 m.	Irregular occurrences of water. Prolific aquifer in Al Hasa.
		Hadrukh		Marly sands, siltstones and sandy limestones	0-90 m.	
	Eocene	Dammam	Alat	Limestone with sandy fissures; orange marl at the base	0-85 m.	Moderate aquifer
			Khobar	Skeletal-detrital limestones, dolomitic limestones; marls at the base	0-60 m.	Aquifer
			Alveolina Limestone	Limestone interbedded with marls or shales	0-20 m.	Aquitard
			Saila Shale Midra Shale	Dark-coloured fissile shales and marls with small gypsiferous lenses	0-25 m.	Aquitard
		Rus		Marl, chalky limestone, anhydrite	10-200 m.	Aquitard
	Paleocene	Umm Er Radhuma		Limestone, dolomitic limestone and dolomite	200-600m.	Aquifer
Cretaceous		Aruma		Limestone; subordinate dolomite and shale	400-600m.	Poor aquifer

In general, each of the aquifers has an established hydraulic gradient that decreases, with fair uniformity, to the north and east. In the same direction, salinity grades from good to poor quality. The gradients follow the regional dip of the sedimentary rocks off the margin of the Arabian Shield (Naimi, 1965). Those water-bearing formations usually serve as conduits for transmitting water from outcrop regions into artesian areas and pressure release points, such as springs and wells (Humaidan, 1980).

Al-Hasa springs derive their water from the Neogene aquifer complex through numerous fractures in the impervious overlying strata. Such fractures permit the confined water under hydrostatic pressure to emerge above the ground surface as free flowing springs. It is hydrologically found that most of Al-Hasa springs are interconnected by a network of tunnels (Liechtweiss Team, 1977). This means that excessive withdrawal from some springs would reduce the natural discharge rate from the others.

According to one of BRGM studies, the Neogene aquifer is not hydrologically independent of underlying water-bearing formations. Alat and Khobar aquifers, the main members of Dammam group present in Al-Hasa, have direct contact with both the underlying Umm er Radhuma and the overlying Neogene aquifers. In all probability, this implies that any increased pumping from the Neogene or any other aquifer in Al-Hasa would affect the whole hydrological system of the Oasis (BRGM, 1977). Inventories of springs and wells that supply water to Al-Hasa Oasis were carried out in different years. This is shown in Tables 3.2 and 3.3. It is worthy to note that most of the old and and new wells tap the Neogene aquifer, and only few tap Al-Khobar and Umm er Radhuma aquifers. In fact, about 75-80% of Al-Hasa groundwater originates from the bulk of the Neogene, and about 10-15% is derived from Khobar and Umm er Radhuma aquifers. In this regard, Neogene is considered the major aquifer and Khobar formation comes in the second place (Al-Taher, 1987).

A detailed description of the springs, their productivity, and locations is especially given in Wakuti's studies (Wakuti-Consulting Engineers, 1964). Of those defined by Wakuti - among others- Figure 3.3 shows the "still-remaining" springs in the Oasis. Wakuti gathered these data by thorough investigations to obtain basic information for the design of the new irrigation and drainage system.

Al-Hasa Irrigation and Drainage Improvement Project (HIDIP), is supplied by water from 32 springs. These spring can be divided into two groups and three single springs. The springs are generally located along Al-Hofuf - Al-Mubarraz - Mutairifi axis. The main springs lie close to the 145 meter contour line that runs in a south-western-northeastern direction. Al-Hofuf - Bani Ma'n area contains 22 springs, while Al-Mutairifi has seven. The single springs are : Ain (spring) Harrah (near Al-Mubarraz), Ain Jauhariyah (near Battali-yah) and Ain Nasser (near Shaba) (Leichtweiss-Team, 1979).

Table 3.2 Wells and Spring Inventories (After Al-Mahmoud, 1987)

Water Points	AGENCY			
	Vidal (1951)	Wakuti (1964)	Italconsult (1969)	BRGM (1977)
No. Wells	5	336	887	689
No. Springs	62	162	102	195

Table 3.3 Water Wells in the Al-Hasa Oasis According to the Aquifer Tapped, and the Type of Well. (After Al-Mahmoud, 1987)

Well Type	AQUIFER			
	Neogene		Khobar -Alat	Umm er Radhuma
	Drilled	Hand Dug		
Water supply	564	83	19	4
Observation	-	-	12	7

No.	Name
1	Khudud
2	Haql
3	Hueire
4	Guedad
5	Umm Save
6	Umm Freech
7	Aseimi
8	Ta' Adhid
9	Amarah
10	Rasibe
11	Talib
12	Barabir
13	Buhadje
14	Umm Allif
15	Manah
16	Luwaimi
17	Umm Dalli
18	Bsetinat
19	Sable
20	Mushaitiyah
21	Jaburiyah
22	Bahlah
23	Huweirrah
24	Hagege
25	Abu Nasser
26	Sumbor
27	Jedide
28	Umm Sabah
29	Nasser
30	Jauhariyah
31	Mansur
32	Harrah
33	Buhairiyah
34	Najim

spring from 1 to 32 are used by HIDA

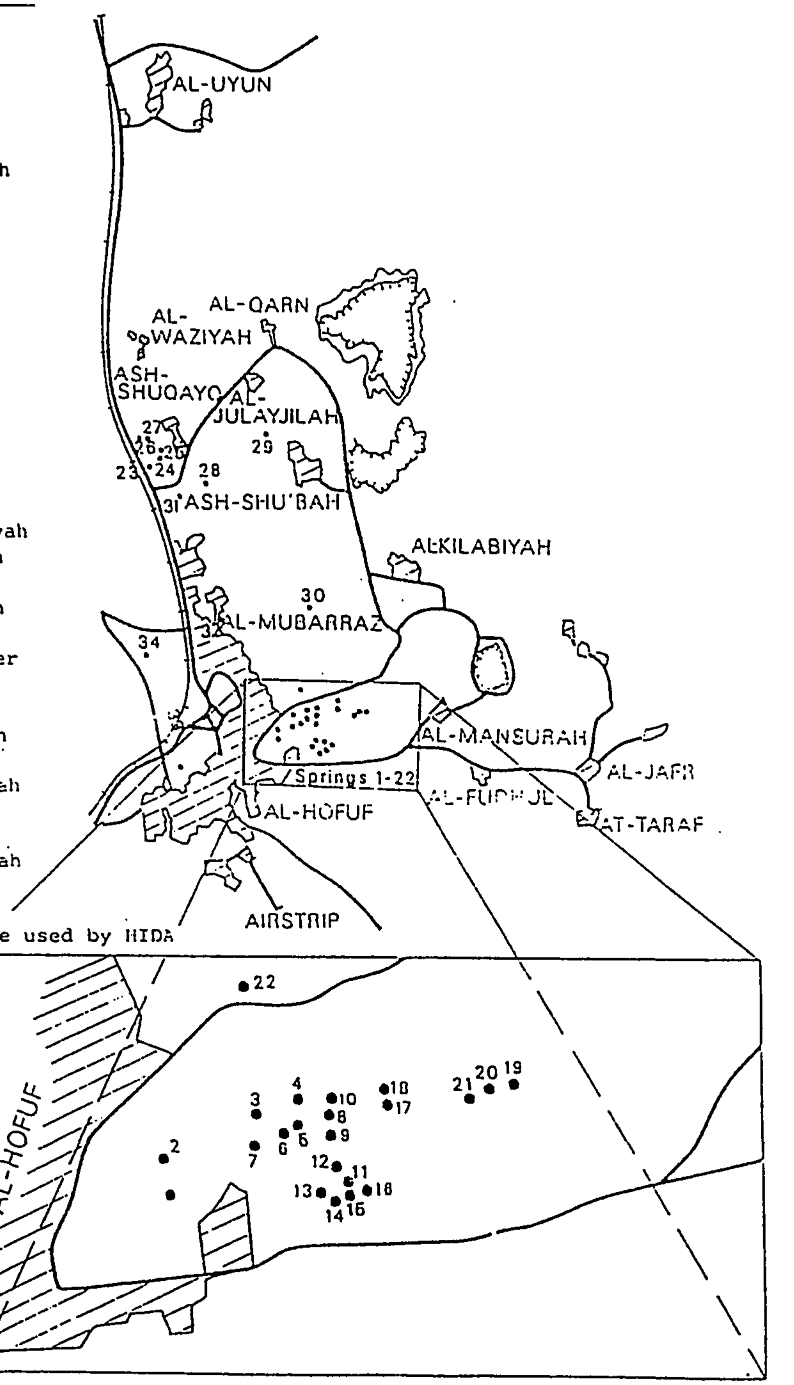


Figure 3.3 Locations of Major Springs in Al-Hasa Oasis (After Al-Mahmoud, 1987)

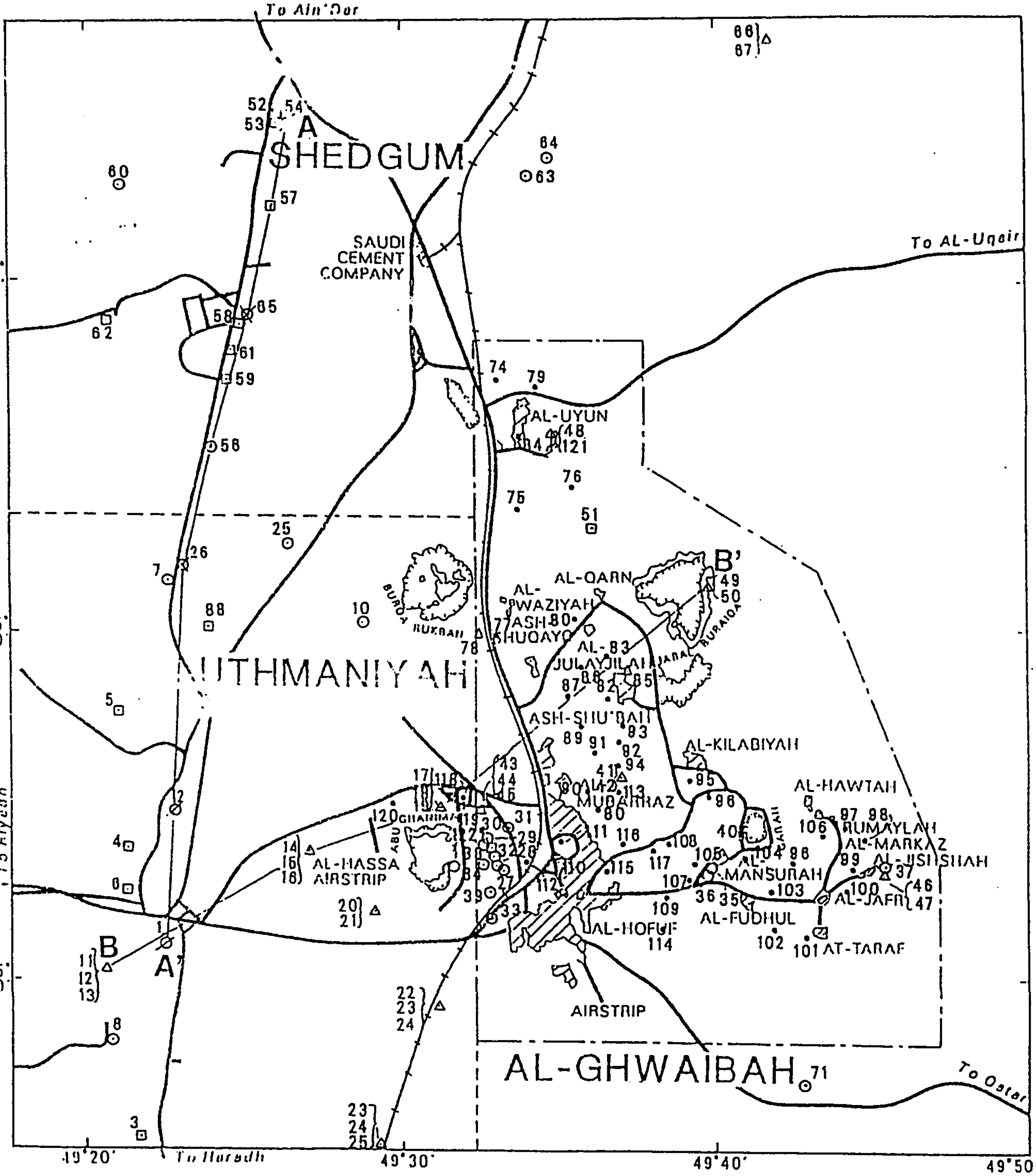


Figure 3.4 Well Locaion Map
(After Al-Mahmoud, 1987)

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
GROUP OF WELLS
SINGLE OBSERVATION WELL
WATER SUPPLY WELL
OIL OR GAS WELL } REFERENCED IN
STRUCTURE WELL } BRGM(1977)
PRIVATE WATER SUPPLY WELL

In 1980, Groundwater Development Consultant (GDC) carried out an inventory of wells existing in Al-Hasa area. In their unpublished report, they mentioned that Al-Ghwaibah area is the "heaviest user" of Al-Hasa groundwater. Most of Al-Ghwaibah's wells tap the Umm er Radhuma and Khobar-Alat aquifers, and are used for irrigation.

During 1984-1986, the *illegal* drilling activities in Al-Hasa Oasis reached a number of about 1500 wells. All of these illegal wells tap the Neogene aquifer. Figure 3.4 shows the locations of legal wells that have been reported by Al-Mahmoud (1987).

3. 3. 2 Aquifer Characteristics

<u>Umm er Radhuma Aquifer</u>

Introduction

The Umm er Radhuma (UER) Formation was named by S. B. Henry and C. W. Brown for the Umm Rad'uma wells (latitude 28° 41' N, longitude 44° 41' E) that draw water from the upper part of the unit (Powers, 1966).

Lithological characters of Umm er Radhuma shows repetitious series of light-colored aphanitic and calcarenitic limestone, dolomitic limestone, and dolomite. The calcarenitic and siliceous are more common in the upper part of the formation and partially dolomitized aphanitic limestone in the lower. The main water-bearing zone is the upper part of the formation due to its porous lattice and loosely cemented dolomite rhumbs. The formation varies in thickness, being 500 meter in the area north of Hofuf and 700 meter further to the east.

Umm er Radhuma is a principal aquifer in eastern Arabia. It is a single thick hydraulic unit of regional extent. Its gradient used to range from water-table conditions near the outcrop to flowing artesian conditions along the Arabian Gulf. The recharge area for this formation is the belt of Aruma and Umm er Radhuma outcrop in addition to the area mantled by Ad Dahna' sand (Powers, 1966).

Production

Umm er Radhuma was not utilized in Al-Hasa prior to 1969 (Italconsult,1969). Since that, many wells have been drilled around Al-Hofuf and Jabal Qarah. Before 1975, the total discharge from these wells was about 0.01 m^3/s (cubic meters per second) and reached a value of 0.05 m^3/s (*BRGM*, 1977). Since 1977, drilling activities, whether *legal* or *illegal* have been increased in the Oasis in general and in Al-Ghwaibah area in particular. Previous estimates of the total pumpage from Umm er Radhuma did not take into account the water abstraction at Al-Ghwaibah. And, unfortunately, neither old estimates nor new ones are published (Al-Mahmoud, 1987).

Hydraulic Properties

Umm er Radhuma is only one aquifer in a complex sequence of aquifers and aquitards in which flow takes place under both lateral and vertical gradients. Lateral flow is predominant in the aquifer units. Hence, looking at Umm er Radhuma in isolation would not lead to proper understanding of its flow regime (Bakiewicz et al. (1982), Milne et al. (1982), Noori et al. (1982)).

The water-bearing characteristics of Umm er Radhuma are mainly controlled by the lithology of the formation and development secondary features such as fissures, joints and solution voids. It is the large secondary openings which make the local high transmissivity of this aquifer. The very high incidence of secondary openings appears to be associated with the Ghawar anticline. Thus, Umm er Radhuma has higher transmissivity values on the crest of the anticline due to the development of secondary permeability by fracturing, and lower transmissivities in the low areas due to the low permeability of the formation (Al-Mahmoud, 1987).

ARAMCO and BRGM performed three *pumping tests* at Uthmaniyah, Hofuf and Jabal Buraiqa. The tested wells (Well Numbers : 11, 49, and 34) are located at different distances from the crest of the Ghawar anticline. Locations of wells used in the three pumping tests are shown in Figure 3.4. Al-Mahmoud (1987) analyzed the drawdown data. Table 3.4 summaries his analysis.

TABLE 3.4 Pumping test data and results for Umm er Radhuma aquifer

Location	*Well No.*	*Test Duration [Days]*	*Average Discharge [l/s]*	*Calculated Transmisivity [m^2/s]*	*Storage Coefficient*	*Remarks*
Uthmaniyah	12	22	40	6.1×10^{-1}	1.2×10^{-4}	-
Hofuf	28	27	73.6	5.5×10^{-3}	6.9×10^{-6}	Early test data
				2.9×10^{-3}	1.1×10^{-5}	Late test data
	9 & 30	27	73.6	1.1×10^{-2}	-	Early test data
				5.5×10^{-3}	-	Midle test data
				2.8×10^{-3}	-	Late test data
Jabal Buraiqa	49	0.125	1.75	6.8×10^{-4}	-	-

Source: (Al-Mahmoud, 1987)

Groundwater Monitoring Data

Eight water level hydrographs were available for Al-Mahmoud (1987) to analyze the historical behavior of the Umm er Radhuma water level. Most of the data cover the whole area in the period 1977-1984. Unless otherwise stated, the following will depend on Al-Mahmoud's analysis.

Historical Water Level Behavior

Observation wells No. 8 and No. 12 are located in Uthmaniyah. The high transmissivity value in that area explains the insignificant seasonal or long-term variations in Umm er Radhima water level.

Hydrographs of observation wells No. 10, 28, and 71, which are located on the eastern flank of the Ghawar anticline are shown in Figure 3.5. The Figure shows a pronounced water level decline starting in 1978 and thereafter. The drop is caused by vast pumping in Al-Hasa Oasis and Al-Ghwaibah area. The recharge at these particular areas, which takes place in winter, is much less than the excessive discharge (whether in winter or in summer) due to low transmissivity at both locations. The water level decline in the period 1978-1984 varies from one place to another, depending on the withdrawals in the area. In Al-Hasa Oasis, a maximum of 30 meters drawdown was recorded in the southern part of the Oasis.

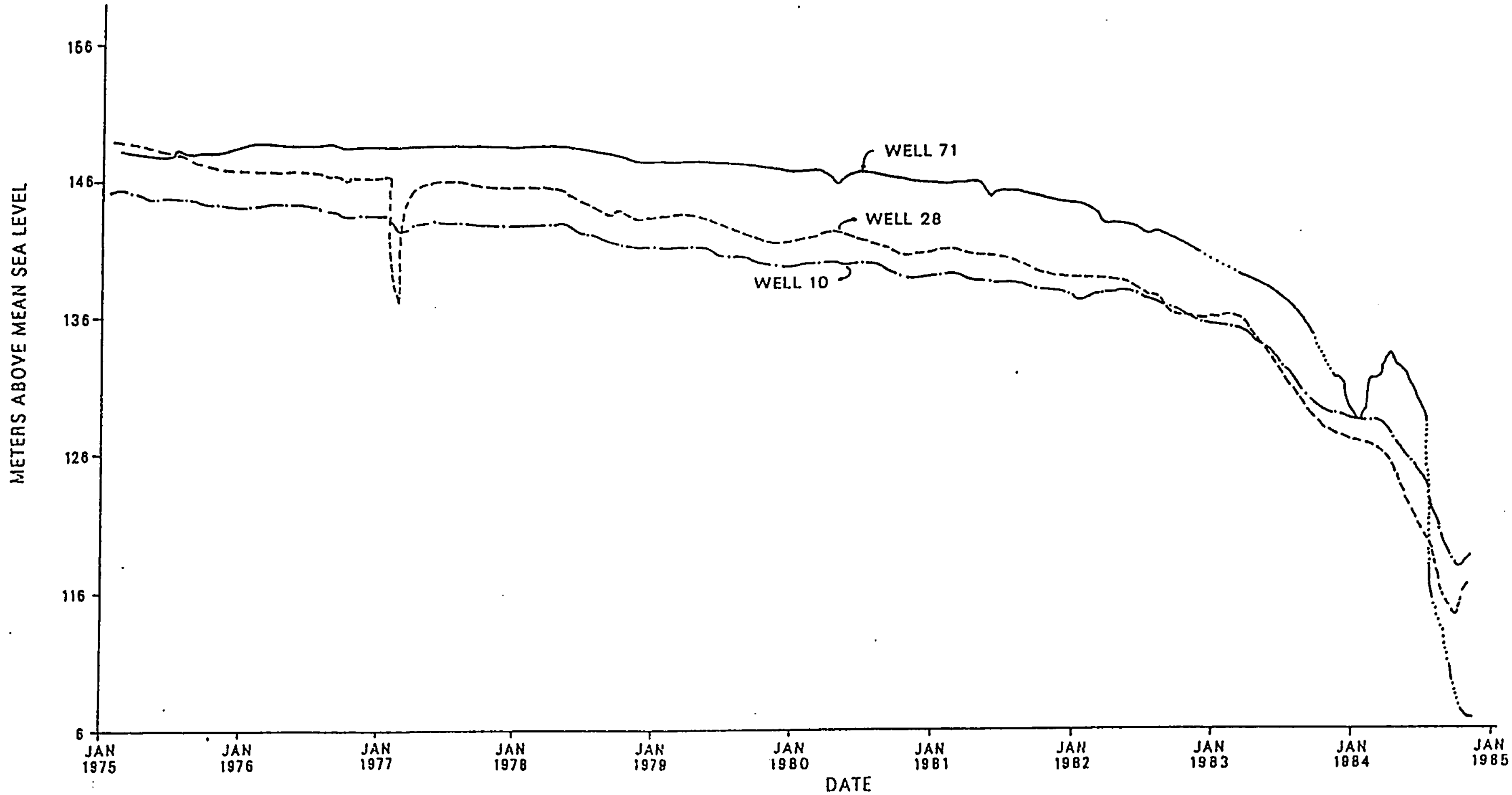


Figure 3.5 Water Level Hydrographs of Wells 10, 28, & 71 (After Al-Mahmoud, 1987)

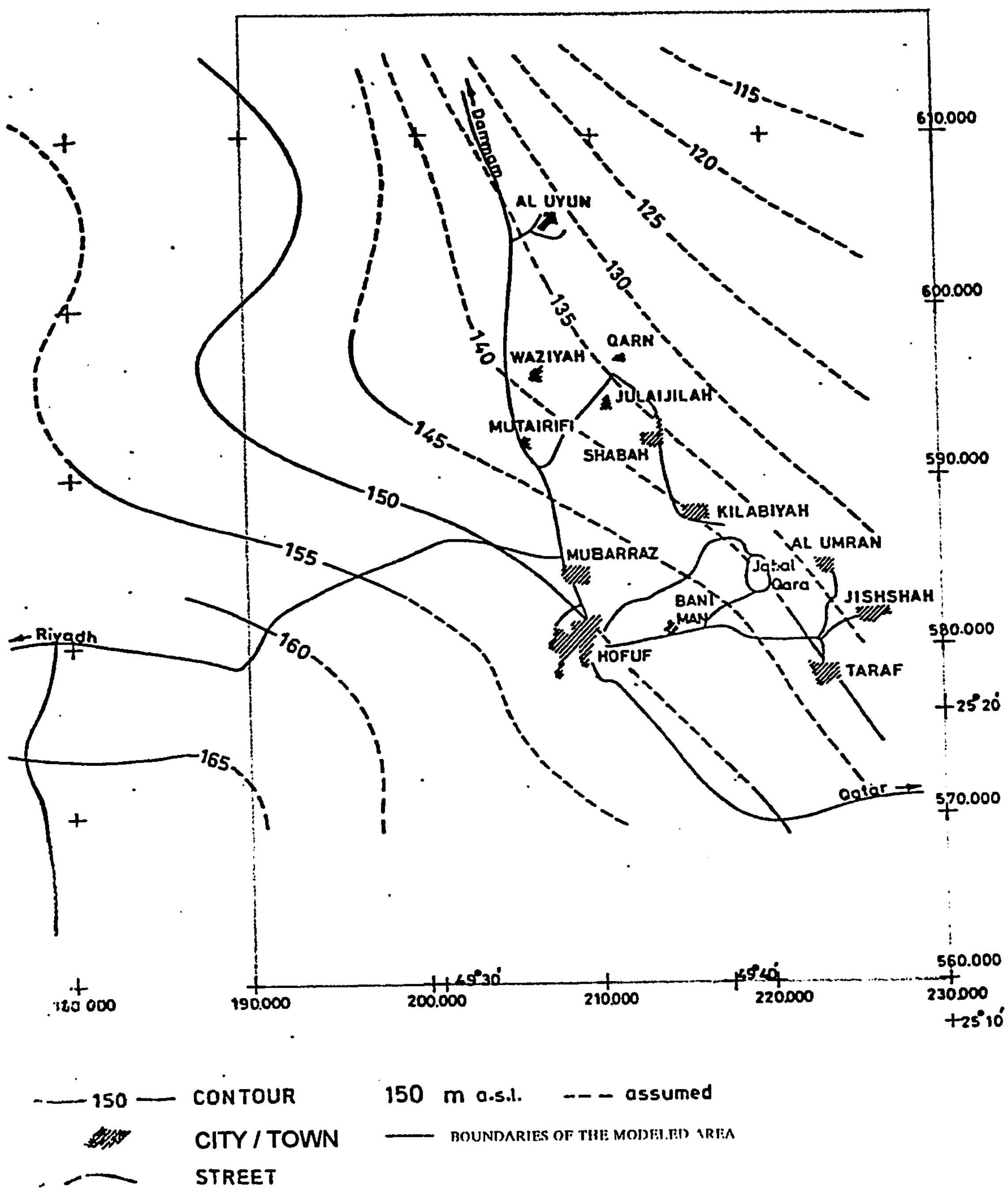


Figure 3.6 Piezometric Map of the Umm er Radhuma Aquifer (After BRGM, 1977)

0 5 10 KM

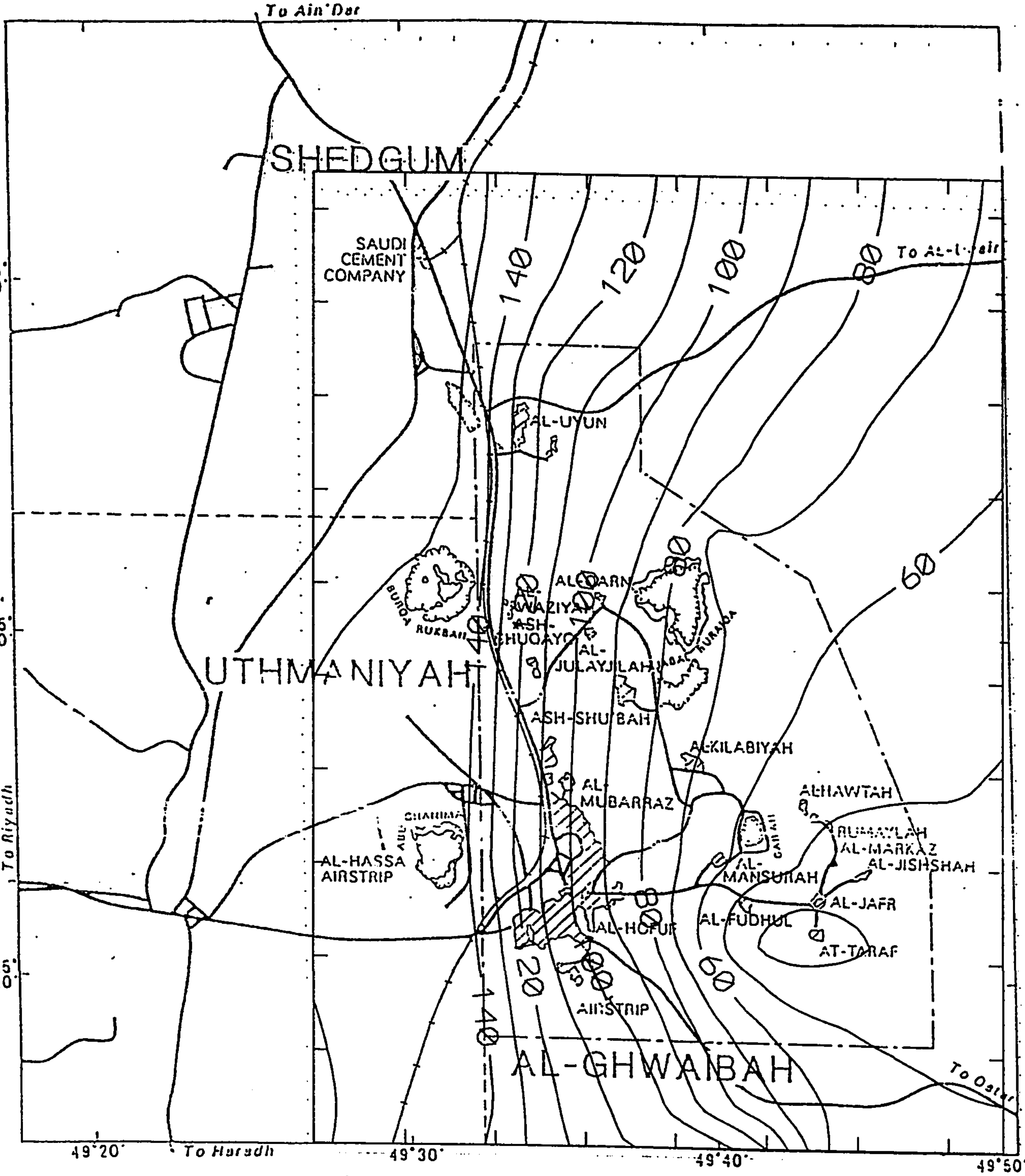


Figure 3.7 : Piezometric Surface Map of Umm Er Radhuma Aquifer for the Year 1983-1984

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

Spatial Water Level Behavior

In their report "Water Potential of the Al Hassa Oasis", Leichtweiss-Team (1979) studied water levels in Umm Er Radhuma. Figure 3.6 is a piezometric map of Umm Er Radhuma before 1979 drawn according to their study. A more recent map is available for the potentiometric surface of this aquifer, and reflects the water level elevations of observation wells (Figure 3.7). The Figure reveals the presence of a depression cone near Al-Ghwaibah area. The depression cone of Al-Ghwaibah (about 30 meters decline below the regional water level) is thought to be a result of low transmissivity in this area.

Khobar-Alat Aquifer

Introduction

Khobar and Alat aquifers belong to Dammam Formation. Their chronological order has been given in Table (3.1). Both Khobar and Alat Limestone Members are persistent in the subsurface of Saudi Arabia except in the northeast.

Khobar aquifer is bounded from the top by Alat marl and from the bottom by Khobar marl. It has good hydraulic properties in the coastal area of the Arabian Gulf, where it has been tapped by thousands of wells due to the shallow water depth and the reasonably good permeabilities of its rocks. The limited thickness of the aquifer lowered its storage capacity. Alat aquifer is truncated from the top by the post-Dammam unconformity and is bounded from the bottom by Alat marl. It has high transmissivity values along the Gulf coast, decreasing westward (Al-Najjar, 1986).

Khobar and Alat limestones cannot be studied separately without committing large errors. This is due to the differential weathering and the partial or total erosion, particularly in the Alat (Al-Najjar, 1986). In addition to that, in Al-Hasa Oasis, almost all drilled wells are open to both the Khobar and the Alat limestones. This has resulted in a distribution of the pumping stresses over water in the two limestones units (Al-Mahmoud, 1987). Hence, Khobar and Alat limestones will be treated as one single aquifer.

Production

The total withdrawal from Khobar-Alat aquifer in Al-Hasa was estimated to be 0.032 m^3/s by Italconsult (1969). pumping rates increased to about 0.16 m^3/s (GDC, 1980). Since 1980 and thereafter, water level has shown a continuous decline, which is a direct signal of drilling more and more wells in the Oasis. In no mean it was possible to get any recent records regarding the abstraction rates from Khobar-Alat aquifer (Al-Mahmoud, 1987).

Hydraulic Properties

BRGM and ARAMCO conducted pumping tests at Jabal Abu-Ghanimah, Al-Ghwaibah, Al-Waziyah and east Shedgum. Al-Mahmoud (1987)

Table 3.5 Pumping Test Data and Results for the Khobar-Alat Aquifer (After Al-Mahmoud, 1987)

Location	Tested Well No.	Test Duration [min.]	Average Discharge [l/s]	Calculated Transmisivity [m^2/s]	Remarks
Jabal Abu-Ghanimah	18	150	2.5	3.5×10^{-2}	Well is about 800 meters to the north of Jabal Abu Ghanimah
Al-Ghwaibah	72	480	16.5	4.5×10^{-4}	King Faisal University well no. 2
Al-Waziyah	78	120	1.72	5.1×10^{-3}	Well is about 2 km to the southwest of Al-Waziyah
East Shedgum	67	180	1.75	1.7×10^{-4}	Well is about 24 km to the northeast of Al-Uyun

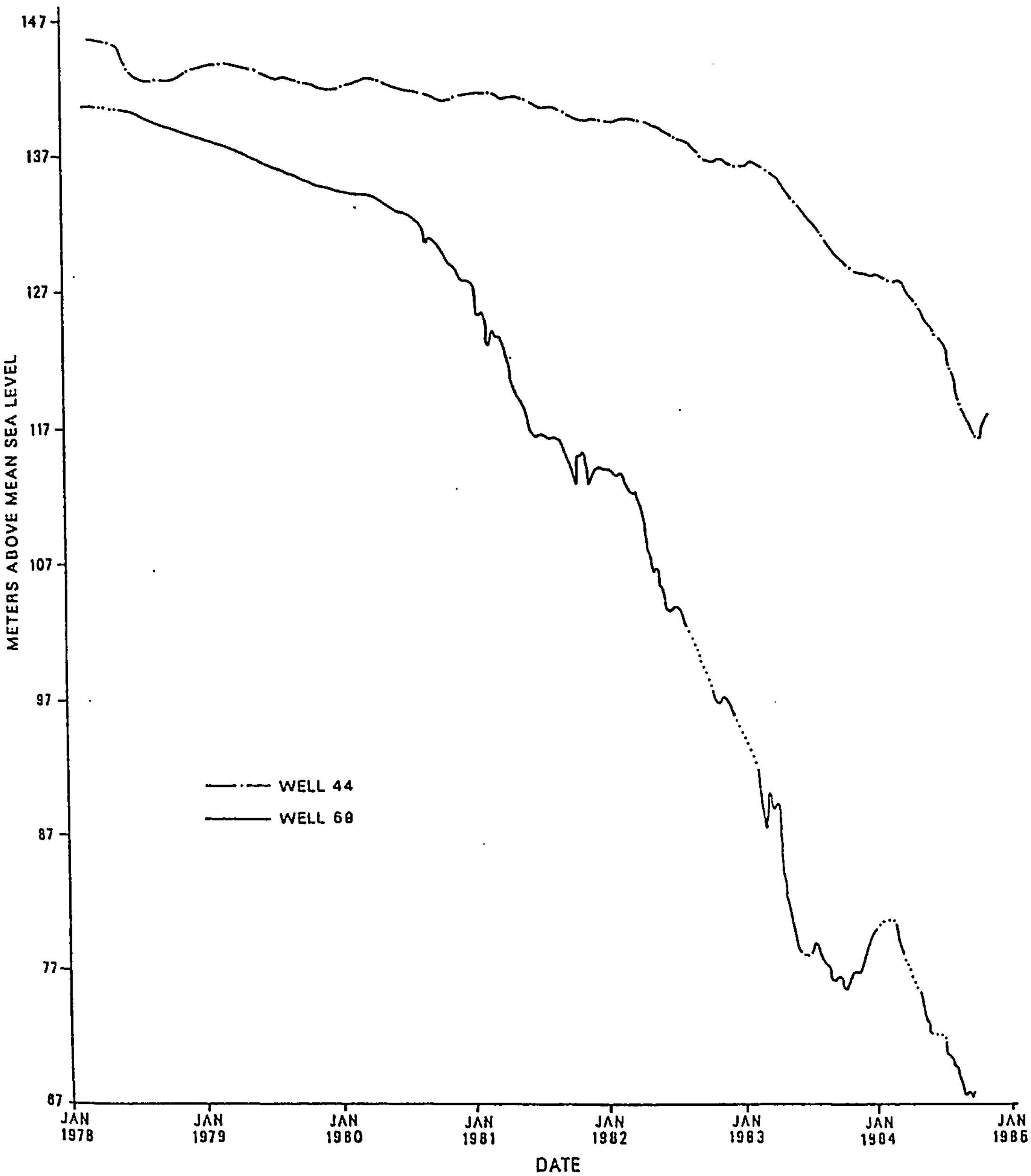


Figure 3.8 Water Level Hydrographs of Wells 44 & 69 (After Al-Mahmoud, 1987)

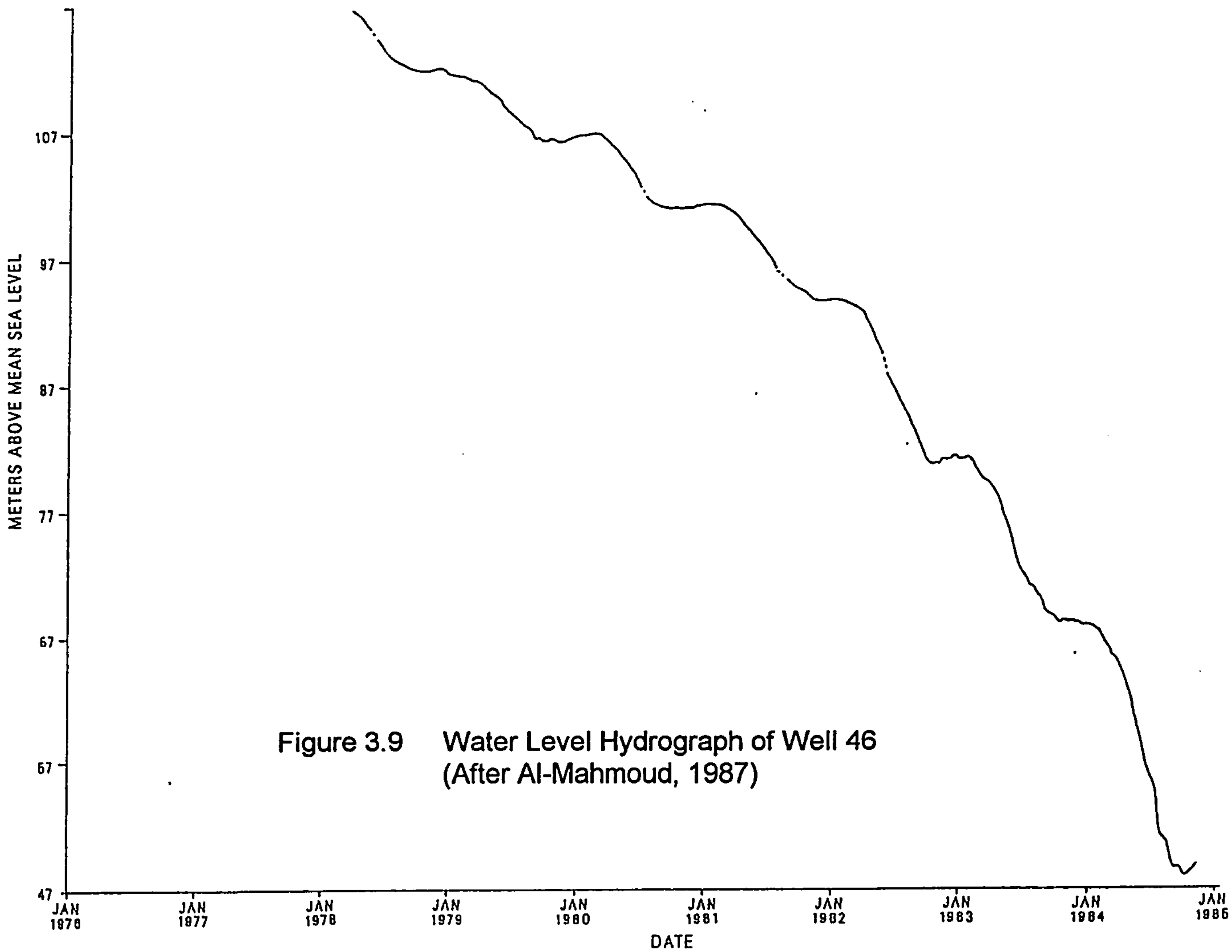
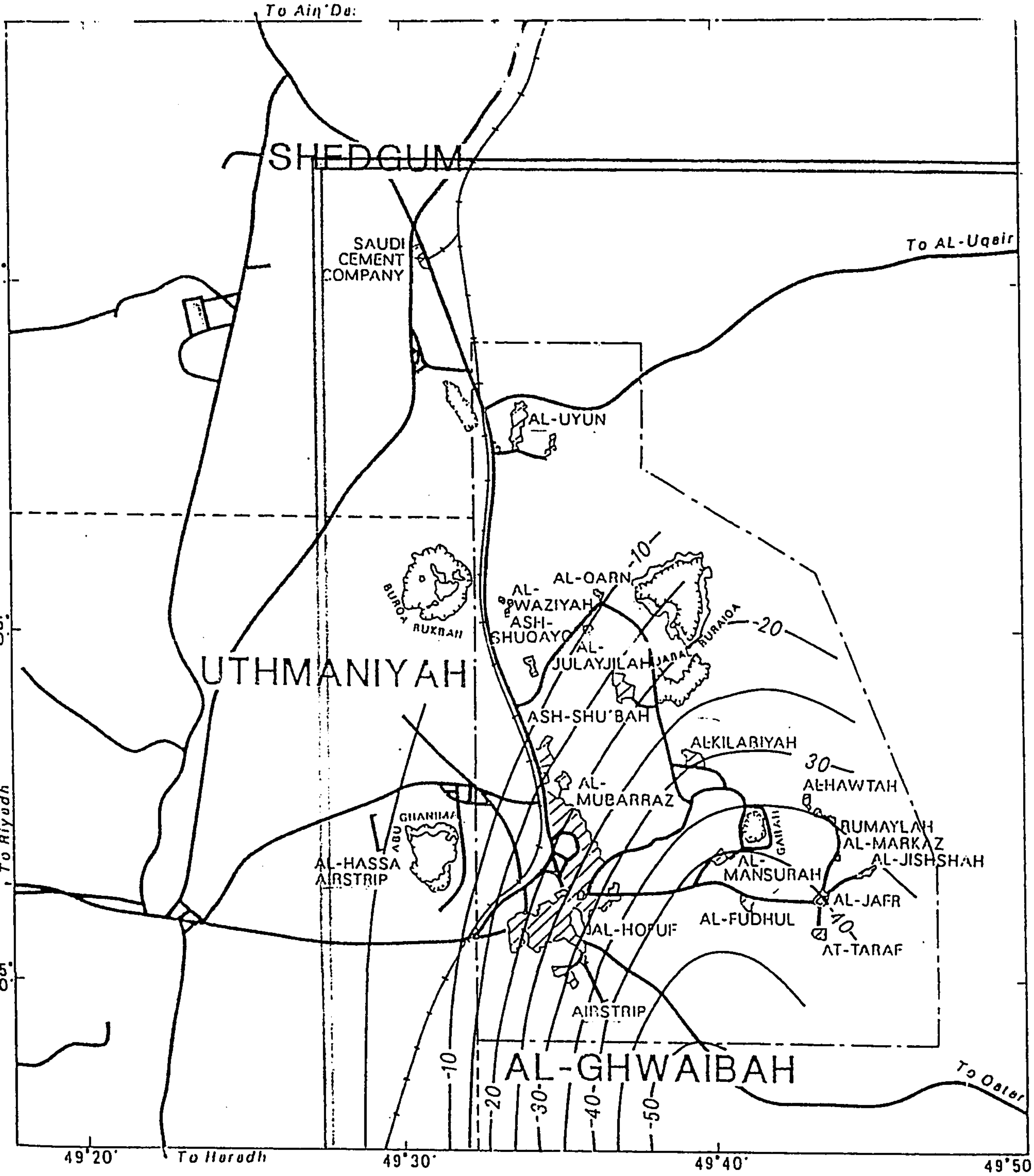


Figure 3.9 Water Level Hydrograph of Well 46 (After Al-Mahmoud, 1987)



FIGURE(3.10): CONTOUR MAP OF THE NET CHANGE IN THE KHOBAR-ALAT WATER LEVEL IN THE PERIOD FROM MARCH, 1978 TO MARCH, 1983
(After Al-Mahmoud, 1987)

3 0 3 6 9 12
KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
-50- CONTOUR LINE OF THE AMOUNT OF CHANGE IN WATER LEVELS. THE AMOUNT OF CHANGE IS 50 METERS
CONTOUR INTERVAL = 5 METERS
BOUNDARIES OF THE MODELED AREA

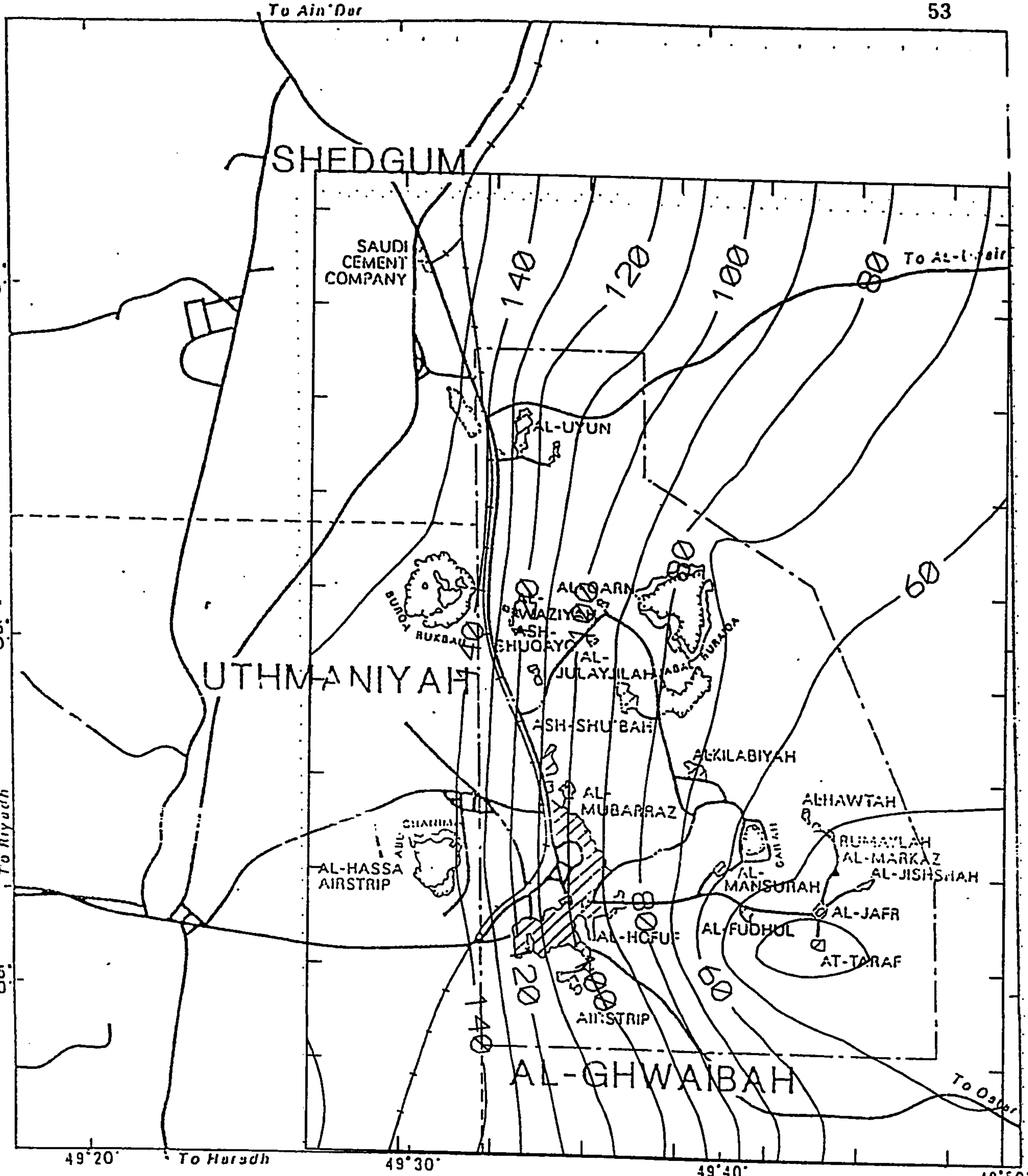


Figure 3.11 : Piezometric Surface Map of Khobar-Alat Aquifer for the Year 1983-1984

3 0 3 6 9 12
KM

EXPLANATION
- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

interpreted the obtained drawdown data and calculated the transmissivity values that are shown in Table (3.5). As it was the case with the Umm er Radhuma, transmissivity of Khobar-Alat aquifer increases towards Ghawar anticline crest. This is attributed to the increased fracturing density of the aquifer rocks in that direction.

Groundwater Monitoring Data

Historical Water Level Behavior

Hydrographs of observation wells No. 44, 69, and 46 (Figures 3.8 and 3.9) give the water level in Khobar-Alat aquifer. a *drastic fall* is to be observed in the water level in the period of 1978-1983. The amount of decline is about 30 meters in the western part, 70 meters in the east of the Oasis, and 77 meters in Al-Ghwaibah area. The greater drawdowns in the eastern part of the Al-Hasa and Al-Ghwaibah is due to the fact that most of the irrigation and domestic supply wells that tap Khobar-Alat formation are located in these two areas. Figure 3.10 gives the net change in this aquifer for the same period (1978-1983), and enhances that pumping in Al-Ghwaibah is the major cause of the water level decline.

Spatial Water Level Behavior

Khobar-Alat potentiometric surface is shown in Figure 3.11. The Figure reveals a relatively high gradients between Uthmaniyah (west of Hofuf) and Al-Ghwaibah. The heavy pumping in the Al-Ghwaibah and the southern part of Al-Hasa Oasis has shifted the general eastward flow.

Neogene Aquifer

Introduction

Based on lithology, the Neogene Aquifer in Al-Hasa is divided from top to bottom into three formations : Hofuf, Dam, and Hadrakh (Table 3.1). It is practically the only formation in outcrop. Its rocks are predominantly sandy limestone and sandy marl.

Water is encountered over a wide area, but the productive capacity of the aquifer is unreliable. The formation changes rapidly its porosity, permeability and water quality (Naimi, 1965).

Production

Al-Hasa Oasis is one of the major Neogene development areas. The aquifer supplies many of the drilled wells and springs in the Oasis, and artesian conditions used to prevail (Naimi, 1965).

Before 1972, discharge estimates were based on discontinuous short-term flow measurements from springs and wells. Vidal (1951), estimated the springs discharge rate at 9.5 m^3/s. On the basis of longer-histories measurement, Wakuti (1964) and Italconsult (1969), estimated the discharge rates from the Neogene aquifer in Al-Hasa Oasis at 14.1 m^3/s and 13.4 m^3/s respectively. Tables 3.6 and

TABLE 3.6	Estimate of discharge rate from the Neogene aquifer at the Al- Hasa Oasis			
	Discharge Rate [cubic meters/sec.]			
Year	Main Springs	Well and Minor Springs	Total	Source of Estimates
1951	9.5*	-	-	Vidal
1964	-	-	14.1	Wakuti
1969	-	-	13.4	Italconsult
1971 to 1977	7.1	3.025	10.125	BRGM

* Discharge rate for the 32 springs and some other springs

Source: (Al-Mahmoud, 1987)

TABLE 3.7	Continuous discharge rate from the 32 main springs at Al-Hasa Oasis. (Source: HIDA)
Year	Discharge Rate [cubic meters/sec.]
1975	7.26
1976	7.05
1977	7.41
1978	7.36
1979	7.21
1980	7.52
1981	7.06
1982	6.73
1983	6.91

* Discharge rate for the 32 springs and some other springs

3.7 summarize previous discharge estimates in the period of 1951-1983.

According to Abderrahman and Ukayli (1984), the average discharge rates from wells and minor springs in the years 1980 and 1982 were at 3.781 m^3/s and 4.208 m^3/s respectively. If this is added to the pumpage rates utilized by Al-Hasa Irrigation and Drainage Authority (HIDA) for the same period (Table 3.7), this gives a total abstractions of 11.301 m^3/s and 10.938 m^3/s respectively. These amounts are 7 % and 4 % (7 per cent and 4 per cent) higher than 1977 values. HIDA records for the period of 1984-1986 showed that 1500 *illegal* wells were drilled in the Neogene aquifer with a total discharge of 2.5 m^3/s (*HIDA*, 1986).

Hydraulic Properties

Data on hydraulic properties of the Neogene aquifer has been obtained from one pumping test and from specific capacity data provided by previous investigators.

A pumping test was conducted at well No. 38 by ARAMCO in 1985. The well is located 6 kilometers west of Al-Mubarraz, as seen in Figure 3.4. The late drawdown data analysis gave an average transmissivity of $1.3 \times 10^{-2}\ m^2/s$ which can be considered typical for the Neogene aquifer in the southwestern part of Al-Hasa Oasis. But, this value does not represent the Neogene transmissivity in the whole area because of the relatively great facies changes of the aquifer (Al-Mahmoud, 1987). Figure 3.12 is a map of the specific capacity pattern of the Neogene aquifer. It can be seen from the map that the highest specific capacity values are in the vicinity of the southwestern parts of Al-Hasa: Jabal abu-Ghanimah, Al-Hofuf, Al-Kilabiyah, and Al-Mubarraz (more than 0.05 m^3/s per one meter drawdown). The lowest specific capacities (less than .01 m^3/s per one meter drawdown) are observed in the north, northeastern, and eastern areas of the Oasis. These trends are, most likely, impacted by the lithology of the aquifer rocks (Al-Mahmoud, 1987).

Groundwater Monitoring Data

Historical Water Level Behavior

The available groundwater monitoring data covers the period 1977-1983. Figures 3.13, 3.14, and 3.15 assure that the seasonal change of Neogene aquifer varies from one place to another. This has to do with differences in withdrawal rates and hydraulic properties of the aquifer. It can be seen that the water level decline decreases gradually from east to west; it took the highest decline of 2 meters in the east while it dropped to 0.6 meter in the center of the Oasis.

In addition to the seasonal variations, the previous Figures dictate that there is a continuous water level decline in the summer periods at the Oasis (about 2.5 meters in Al-Jeshshah) and Al-Ghwaibah area (0.3 meter). This is due to new agricultural and industrial activities in the area.

Spatial Water Level Behavior

Leichtweiss-Team (1979) provided a piezometric map (Figure 3.16) for the Neogene aquifer, depending on the findings of BRGM. Figure 3.17 is the potentiometric surface of the Neogene formation as measured in 1983-1984. Obvious changes are detected from the Figures, but no cones of depression are seen prior to 1979. One cone of depression is shown in 1983 in the southern part of Al-Hasa Oasis. The cone's boundaries do match with the boundaries of specific capacity in the area.

Transmissivity and production rates in the southern part of the Oasis, are higher than those in the other Oasis areas - which make seasonal changes to be low in the south and larger elsewhere. However, in all Al-Hasa Oasis, the Neogene water level is suffering a continuous decline over the years. This is so, because more and more *exploitation* is taking place.

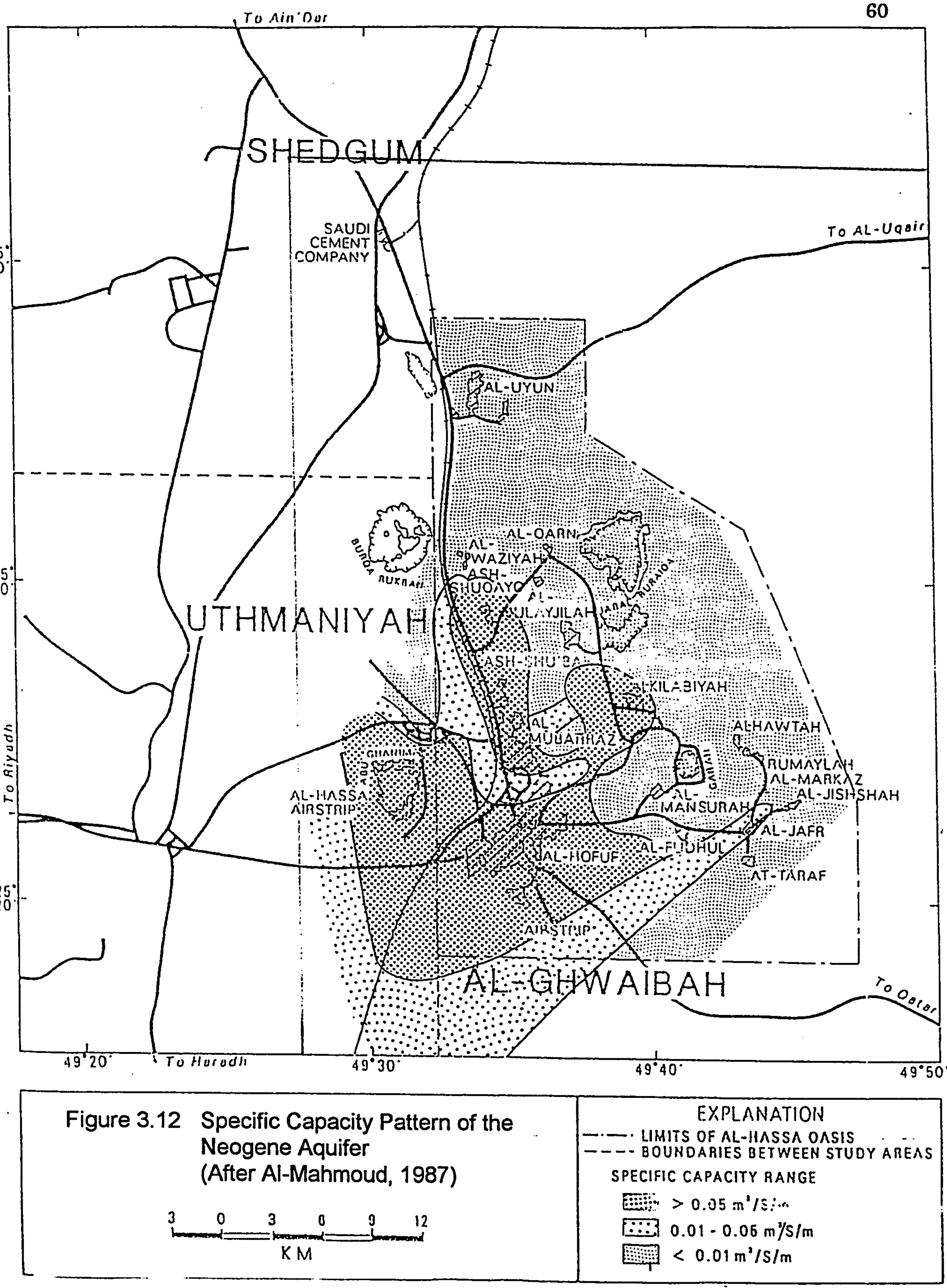


Figure 3.12 Specific Capacity Pattern of the Neogene Aquifer (After Al-Mahmoud, 1987)

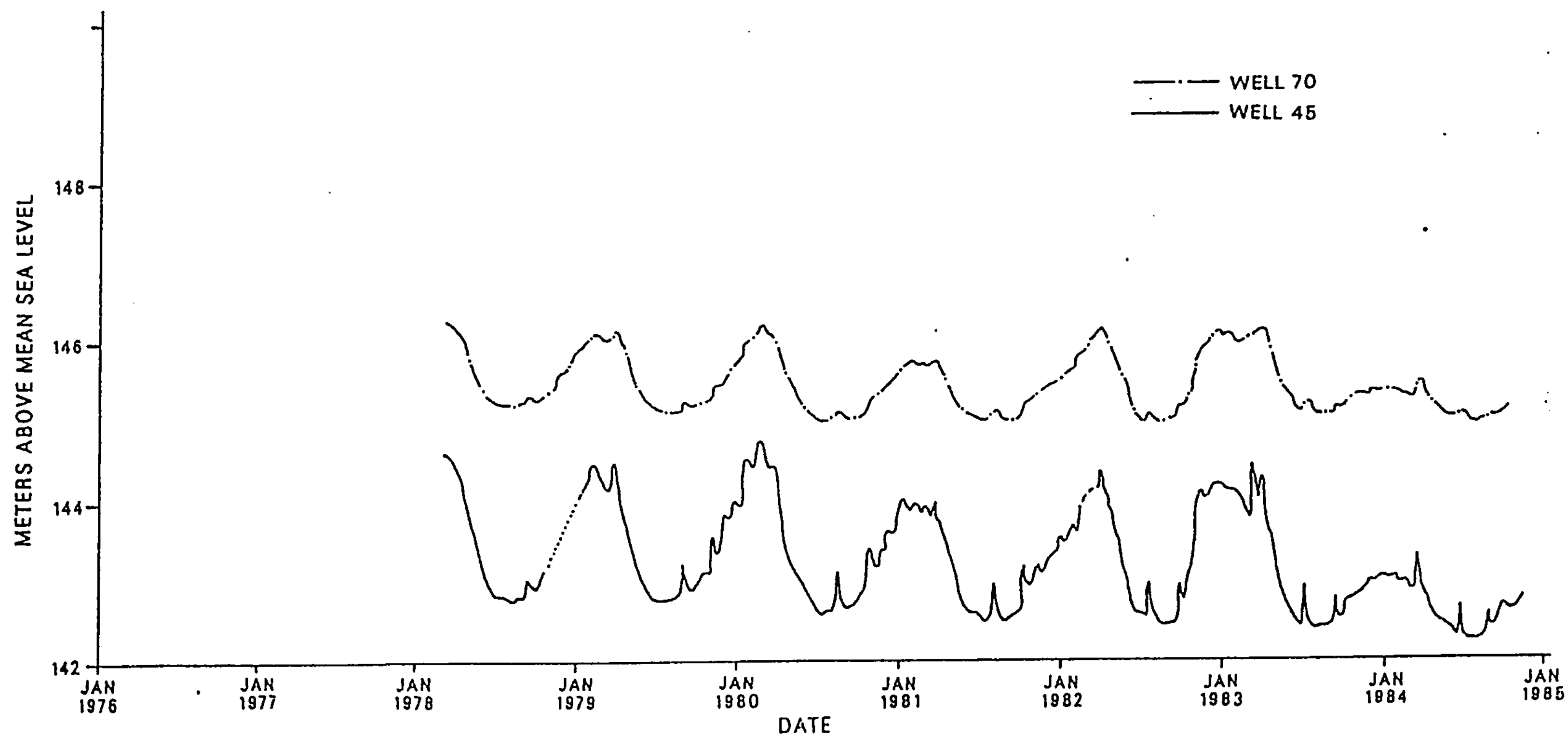


Figure 3.13 Water Level Hydrographs of Wells 45 & 70
(After Al-Mahmoud, 1987)

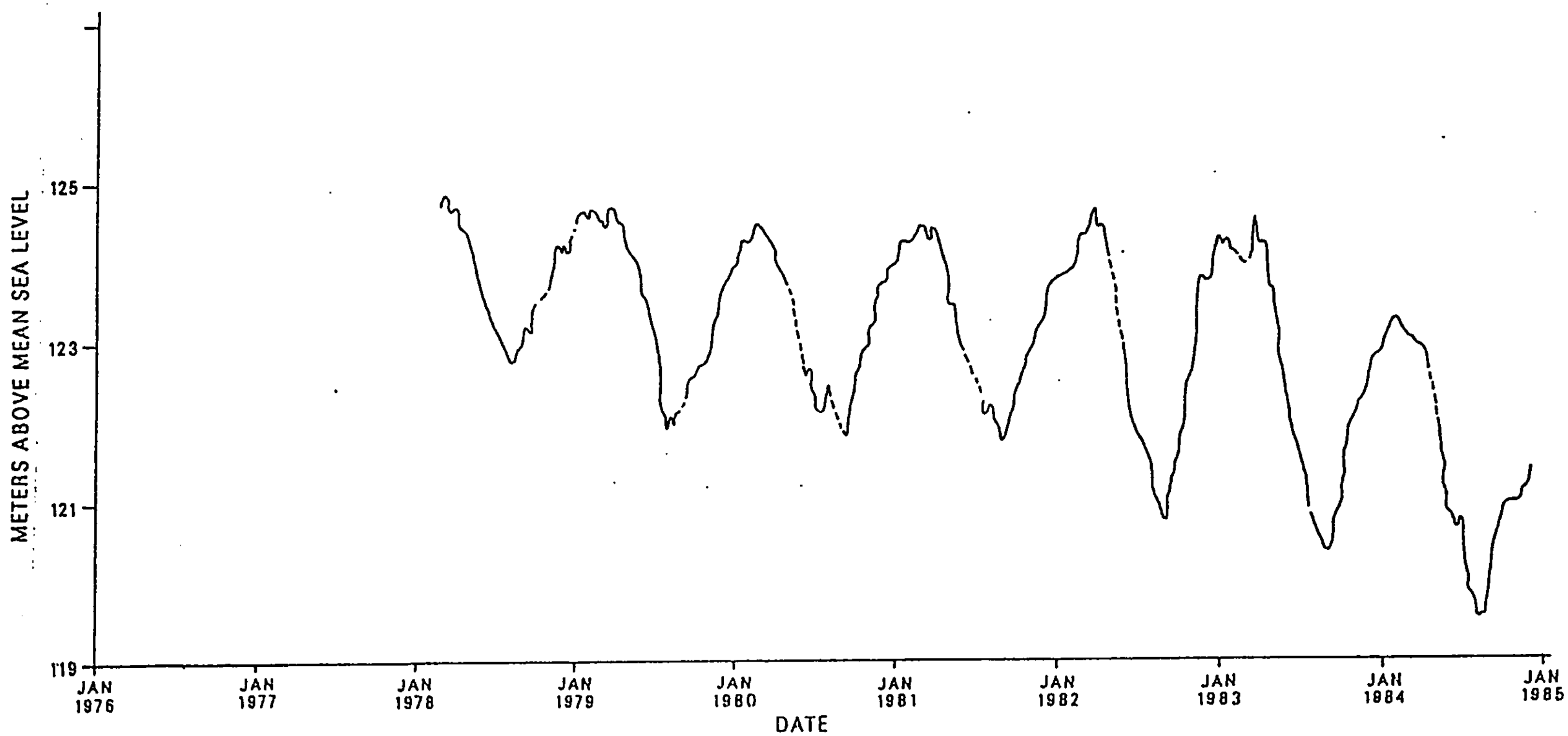
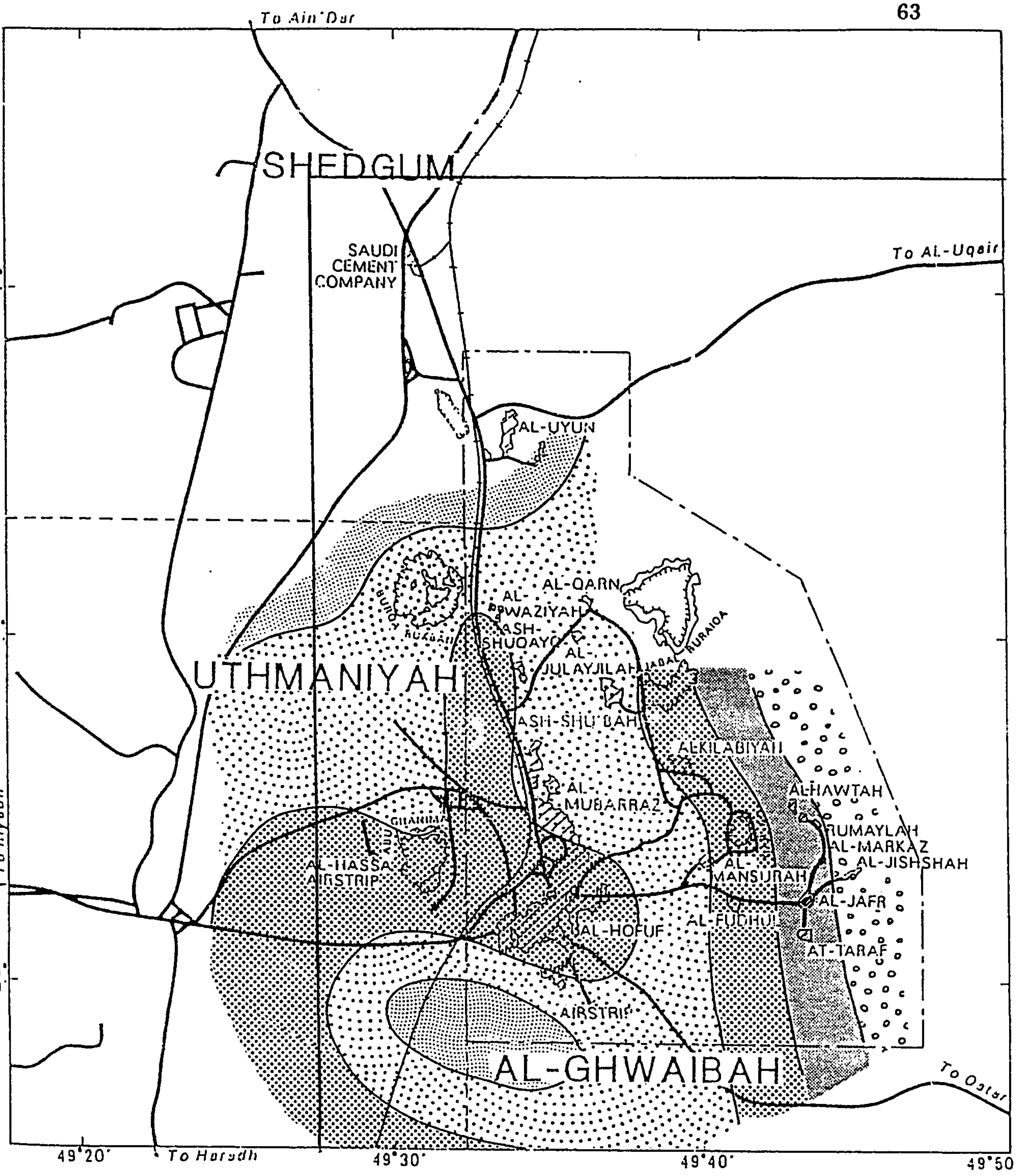


Figure 3.14 Water Level Hydrograph of Wells 47
(After Al-Mahmoud, 1987)



FIGURE(3.15): PATTERN OF THE NET SEASONAL CHANGE IN THE NEOGENE WATER LEVEL (MARCH, 1981 - SEPTEMBER, 1981)

3 0 3 6 9 12
KM

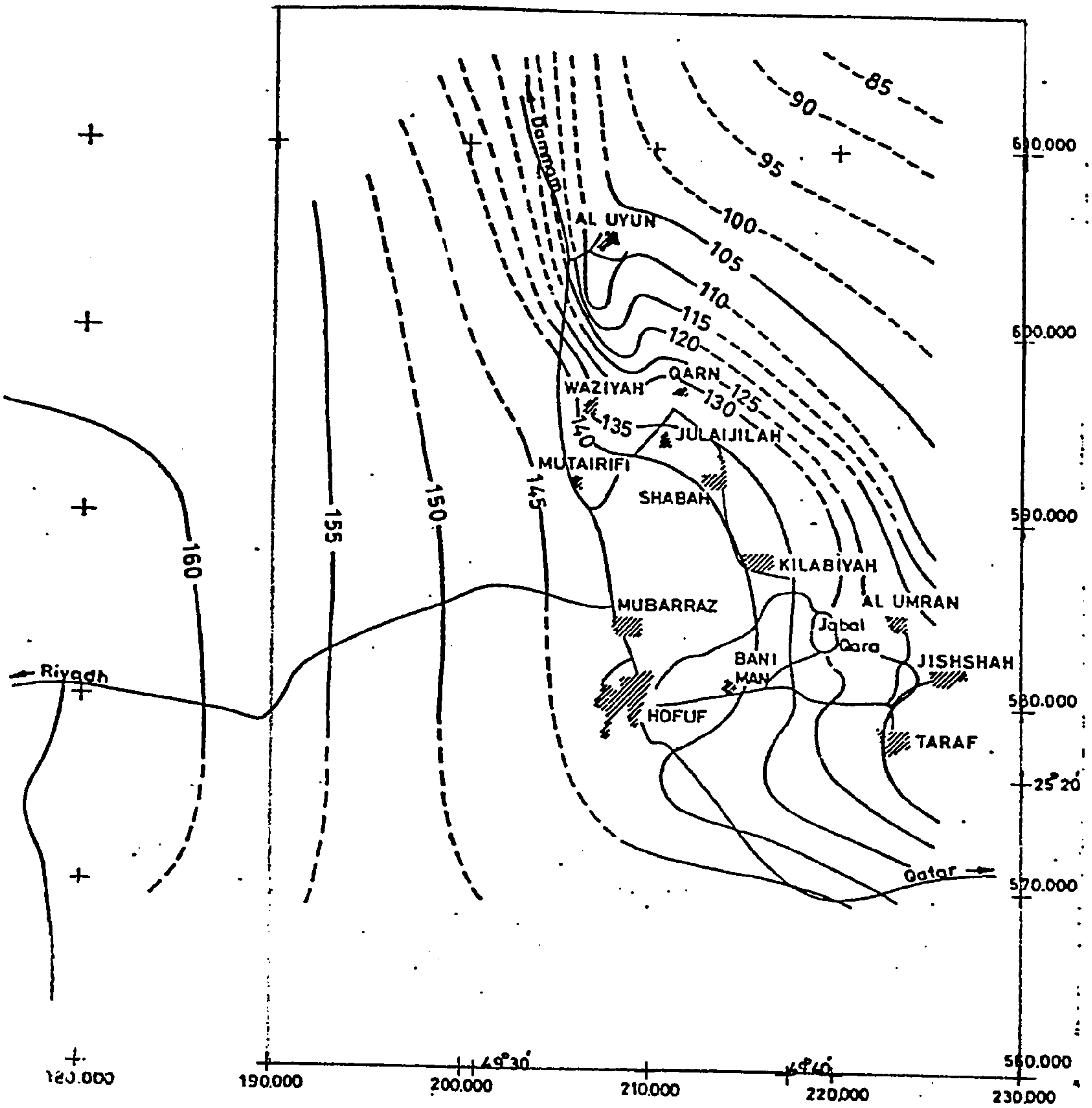
EXPLANATION

—·—·— LIMITS OF AL-HASSA OASIS
- - - - BOUNDARIES BETWEEN STUDY AREAS

RANGES OF WATER LEVEL CHANGES

- > 2 METERS
- 1.5 - 2 METERS
- 1 - 1.5 METERS
- 0.5 - 1 METER
- < 0.5 METER

(After Al-Mahmoud, 1987)



—150—	CONTOUR	150 m a.s.l. ---- assumed
	CITY / TOWN	
	STREET	——— BOUNDRIES OF THE MODELED AREA

Figure 3.16 Piezometric Map of the Neogene Aquifer (After BRGM, 1977)

0 5 10 KM

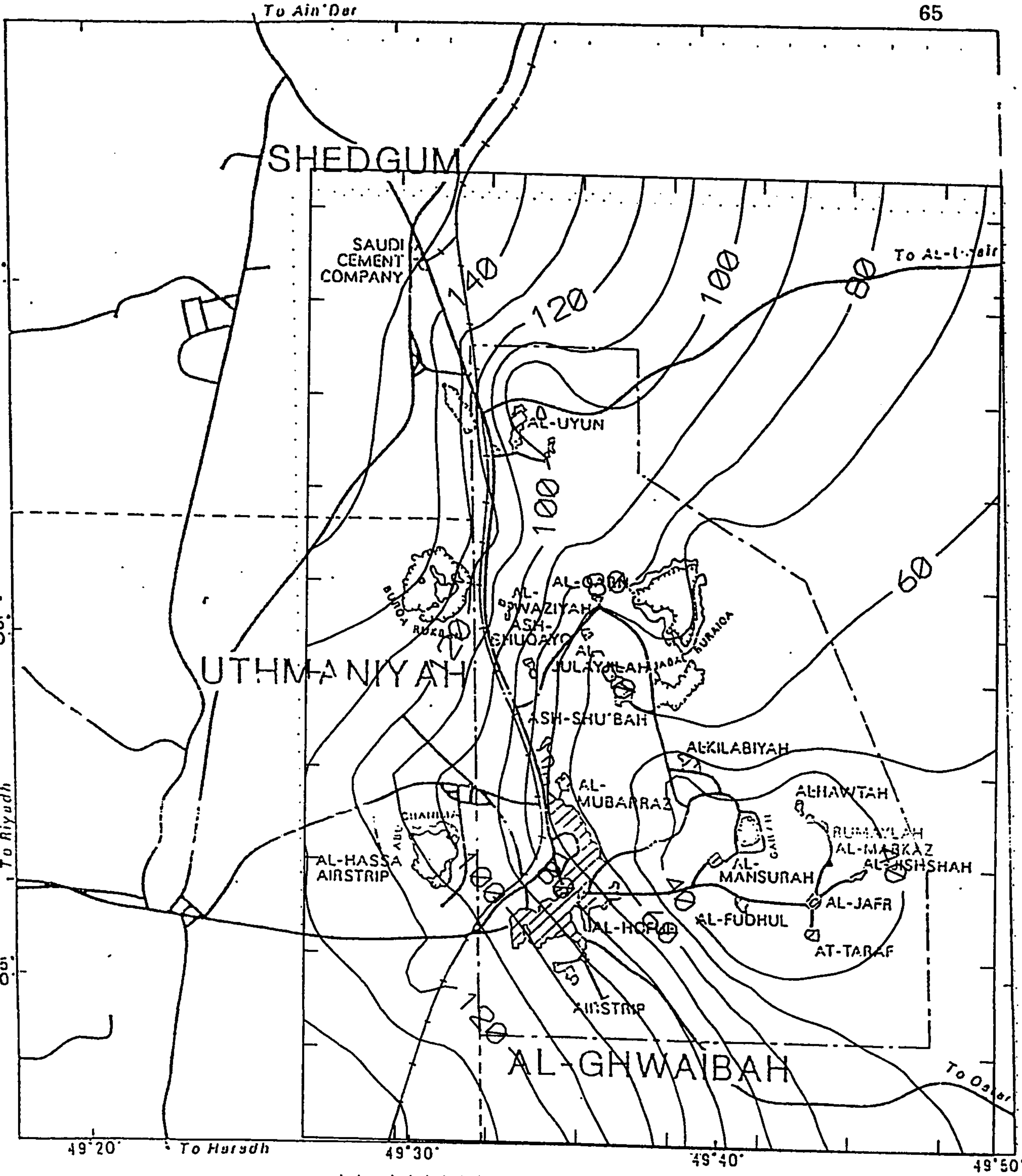


Figure 3.17 : Piezometric Surface Map of Neogene Aquifer for the Year 1983-1984

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

3. 3. 3 Discharge Patterns

The investigations they carried out in 1963-1964 led Wakuti to conclude that Al-Hasa total discharge was 14.1 m^3/s. The discharge components were : 336 wells, free flowing or pumped; 83 small springs, free flowing or pumped; and 42 springs. For each spring, a specific discharge function Q = f(h) (Q : discharge, h : water level) was established by arbitrarily measuring adjusted water levels and the corresponding discharge rates. From "Q versus h" curves, it was concluded that each draw-off of the water level results a consequent increase in the discharge rate.

Wakuti took into consideration neither the possibility of a hydraulic interconnection between the springs nor a possible limitation of the groundwater reservoir. Hence, a discharge of of 14.1 m^3/s (which is equivalent to a yearly supply of $4.45 x 10^8$ m^3) was assumed to be available for Al-Hasa Irrigation and Drainage Project. The water demand for the proposed extension in the arable irrigated land (16,000 hectares) was estimated to be $3.92 x 10^8$ m^3 annually (maximum need : 14.6 m^3/s). But, Al-Hasa Irrigation and Drainage Project was provided by 32 main springs only with a maximum discharge of 10.4 m^3/s. (which is equivalent to a yearly supply of $3.28 x 10^8$ m^3). The deficit in water could be compensated only by more lowering of water levels in the springs. Thus, Wakuti (1964) overestimated the cumulative average discharge of the springs (Leichtweiss-Team, 1979). And, only less than 8,000 hectares (out of planned 16,000 hectares) could be irrigated. In fact, some parts of the irrigation area are suffering severely, in summer, due to water shortages (Leichtweiss-Team, 1979).

Measurements during 1973-1976 reveal that the available water supply was composed of :

(1) Discharge of 32 main springs connected to the irrigation system, operated by HIDA (Al-Hasa Irrigation and Drainage Authority)
   - (a) gravity flow
   - (b) delivery of three pumping stations (P1, P2, P3)
   - (c) delivery of other pumping stations

(2) Delivery of about 600 private pumps, pumping water from wells and springs (not connected to the irrigation system)

Figure 3.18 gives the water measurement stations within Al-Hasa Oasis. Figure 3.19 reflects the relation between pumps delivery, springs discharge, and the total withdrawal in 1973-1976.

Figure 3.18 Water Measurement Stations Within Al-Hasa Oasis
(Source: Leichtweiss Team, Publication no. 38, 1979)

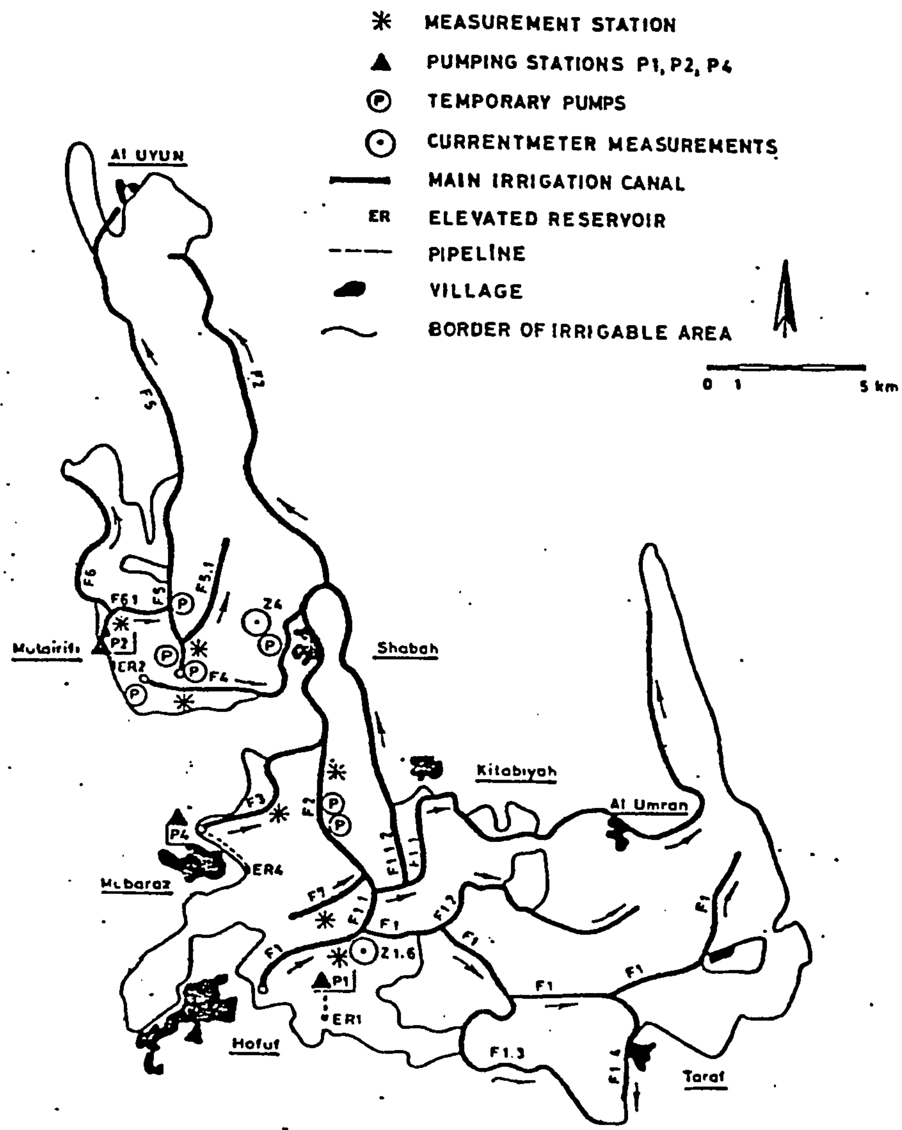
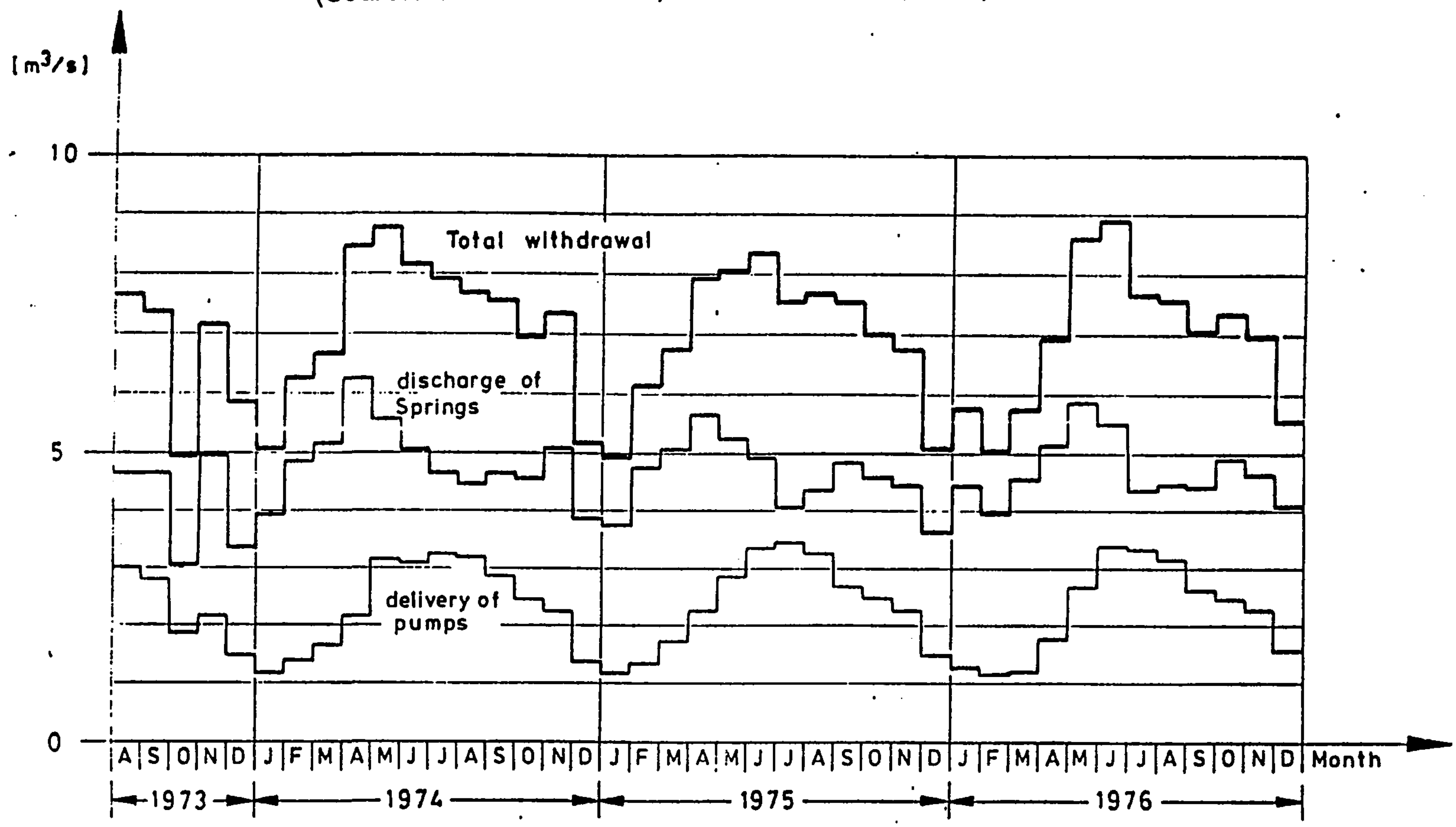


Figure 3.19 Mean Monthly Withdrawal (m^3/s) of 32 Main Springs Within Al-Hasa Oasis
(Source: Leichtweiss Team, Publication no. 38, 1979)



3. 3. 4 Irrigation and Landscaping Practice

Irrigation

Prior to the establishment of Al-Hasa Irrigation and Drainage Project, the prevailing irrigation consisted of two parts :

(1) Surface irrigation with free-flowing water from springs

(2) Surface irrigation by mechanically risen water.

The first kind of irrigation comprised the larger palm-gardens, where several vegetations were grown. The water of the artesian springs was led into the irrigation canals (in Arabic; Masqas) which took it to the palm-gardens and fields. This was a "fresh, clear" water (in Arabic; Hurr). The land-owner whose field was adjacent to a Masqa took his need by leading the water onto his garden. The surplus water of Masqa and that drained after irrigating the garden were gathered in a drainage canal (in Arabic; Munajja). Water from several Munajjas was gathered in another canal (in Arabic; thabr), which brought already used water as irrigation water to other gardens. The process was repeated constantly :
Fresh water canal (Masqa) → irrigation area 1 → used water canal (Munajja) → gathering canal (thabr) → irrigation area 2 → used water canal (Munajja) → gathering canal (thabr) irrigation area 3, and so on, as far as the border areas of the Oasis (Wakuti, 1964). From the last terminal drain, the water flowed into the desert

surrounding, or it was gathered in Sabkahs.

The second type of irrigation (surface irrigation by mechanically risen water) covers smaller areas where vegetables and alfalfa were raised, in addition to few date-trees. However, the cultivation areas irrigated in this style took only a small part of the total surface (Wakuti, 1964).

Since 1971, Al-Hasa Irrigation and Drainage Project has been in full operation. The major components of the project are the irrigation and drainage networks. The *irrigation network* (Figure 3.20) consists of about 1520 km (kilometers) of open reinforced concrete main, sub-main, and lateral canals (Humaidan, 1980) :

(*1*) *Main canals*, of 155 km total length; 110 km have a rectangular cross section, with a clear depth of 1.5 m (meter) and 1 m to 2 m width. The other 40 km are of trapezoidal profile, with an average depth of 1.5 m and a bottom width from 3 to 11 meters.

(*2*) *Sub-main canals*. The total length of these canals is 265 km, with square and parabolic cross sections; about 20 km are squares of 1 m depth and 1 m width. The remaining 245 km are parabolas having 0.85 m width and 1.1 m in height.

(*3*) *Lateral canals*. These are parabolic shape canals totaling to 1,100 km length. They are led 150 m apart, in such a way that irrigation is done on one side only to minimize land leveling. Water is conveyed from lateral canals to adjacent farms via flexible hose siphons, that can be inserted anywhere.

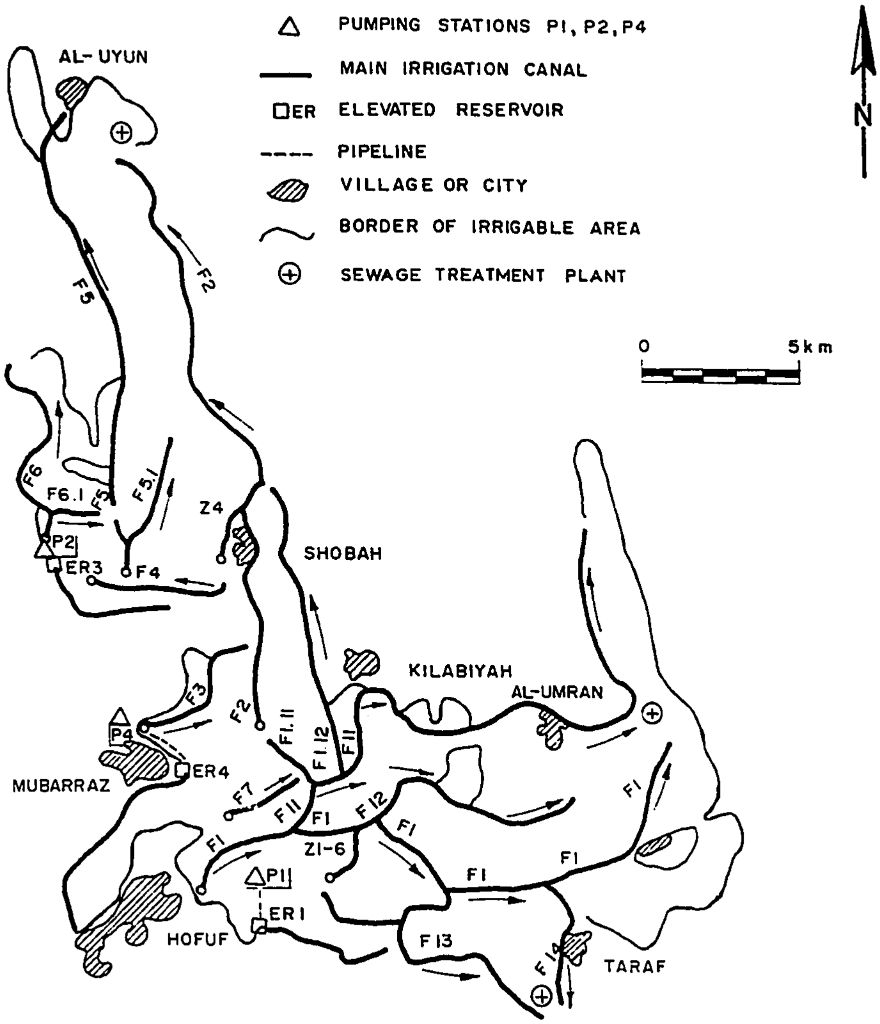


Figure 3.20 General Map of Al-Hasa Irrigation Project and the Main Irrigation System (After Abderrahman, 1988)

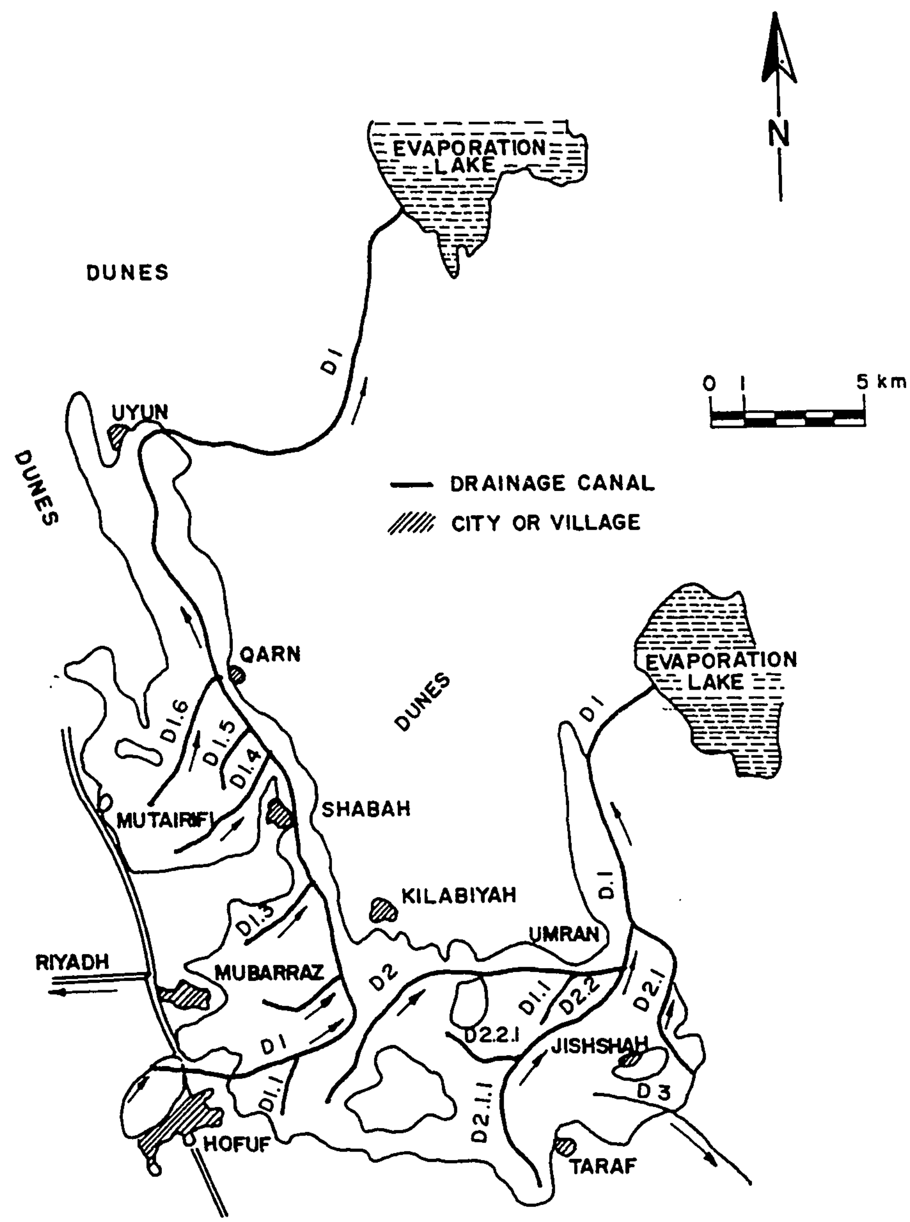


Figure 3.21 Main Drainage System of Al-Hasa Irrigation Project (After Abderrahman, 1988)

The *drainage network* (Figure 3.21) is composed of 1,320 km canal system that is divided into main, sub-main, and lateral canals :

(*1*) *Main canals*, of 140 km length

(*2*) *Sub-main canals*, which are 140 km long

(*3*) *Lateral canals* extending for 1,000 km. Contrast to irrigation system, the drainage water goes from lateral to sub-main and finally to main canals, from where it is conveyed to two drainage lakes outside the Oasis. The ultimate fate of the drainage water is either evaporation or percolation (Al-Taher, 1987).

The project is divided into 10 irrigation districts, each supplied by a main canal fed by separate or grouped springs. Differences in elevations and slope directions dictate that canals not being interlinked and operate as if they are independent from each other (Humaidan, 1980). Seven - of the ten districts - get water by gravity flow serving 16,000 ha (hectares) area. The remaining three districts, covering an area of 4,000 ha, are provided with water from elevated reinforced concrete reservoirs. The water is raised to the reservoirs via pumping from free flowing springs. There are three reservoirs, two of 15,000 m^3 each, and a smaller one of 8,000 m^3 (Wakuti, 1971).

Water is released into lateral canals twice a week in summer and once a week in winter. Farmers may take uncontrolled amounts of water as long as there is water in the canal. The distribution technology within most of the farms is very simple, consisting mainly of small earth barriers that are opened or closed to regulate water diversion from unlined earth ditches (Humaidan, 1980).

Traditional and modern irrigation methods are practiced in the Oasis. Traditional methods persist in the old cultivated areas. They include : Basin irrigation, Furrow irrigation technique, and Border strip method. However, Basin flood irrigation is still the most common due to its simplicity and suitability for various crops. In Al-Hasa Oasis, the basins are generally of small area being 20 m^2 for vegetables and alfalfa and 400 m^2 for growing rice (Leichtweiss-Team, 1975A).

Modern irrigation methods that were introduced in Al-Hasa include Sprinkler and Central Pivot, and Drip (trickle) irrigation. The pros and cons of all these methods- in addition to the traditional methods - as they are applied in Al-Hasa Oasis are discussed by Al-Taher (1987).

Al-Hasa Irrigation and Drainage Authority (HIDA) is the major consumer of Al-Hasa groundwater. The Authority delivers irrigation springs water to about 22,000 farms, comprising a total area of 7,096 hectares (HIDA, 1980). HIDA's records of 1980 showed an annual consumption of 7.1 m^3/s used to irrigate about 8,000 ha. In addition to that 2.5 m^3/s of groundwater was discharged from 140 private minor springs and 562 wells for irrigation, dairy and poultry farms in the region. Hence, the total annual *known* groundwater discharge was about 9.6 m^3/s (Abderrahman and Ukayli, 1984).

Abderrahman (1988), noticed that the water policy of HIDA has two main characteristics :

1. Unbalanced seasonal water consumption

2. Low project efficiency

It can be seen from Table 3.8 that the average winter consumption (October-March) is about 1.74×10^8 m^3 while that in summer (April-September) is around 1.54×10^8 m^3. The actual irrigation demand of winter and summer are 31.8 % and 68.2 % respectively. Thus, a pronounced contrast between "needed" and "practiced" irrigation does exist. This pattern of consumption causes a real exhaustion of the artesian flow to the extent that severe water shortages occur in summer. The above mentioned winter and summer consumptions total to 3.28×10^8 m^3 are used in the irrigation of only 7,096 ha. The remaining 4438 ha of uncultivated (arable) land receive neither enough nor constant amounts of irrigation water (Abderrahman, 1988).

The efficiency of Al-Hasa Irrigation and Drainage Project was calculated by Abderrahman (1988) to be 39 %. The conditions that are responsible for this low efficiency include : uneven water-distribution between irrigation canals due to weak control of sliding gates, variations among farms in irrigation dose and application rate - to mention some factors.

Landscaping Practice

Water, climate, prices, and traditions are the major factors dictating what can be planted in Al-Hasa Oasis and what can not. The cropping pattern has traditionally been oriented towards the production of food crops like dates and vegetables - among others. Alfalfa is the principal forage crops. Table 3.9 shows that date palms, alfalfa, and vegetables cover 93 %, 19 %, and 15 % of the project area respectively. These percentages do not add up to 100 % because of the mixed growing of both alfalfa and vegetables in the date palm areas.

Estimates of land allocation and the total production for the leading crops in the Oasis are given in Table 3.10. In 1972 the date palms was covering about 4121 ha, which is more than 69 % of the total cultivated area. Alfalfa took the second coverage rank of 1134 ha, that stood for over 19 % of the total land. Data for 1982 reflects that the date palms remained the largest area occupier (6738 ha), while alfalfa cultivated area has shrunk to 277 ha (Al-Taher,1987). Official figures prior to 1980 indicated that there were about 1.5 million palm trees in the Oasis. The trees were intercorporated with pomegranates, grapes, limes, and papayas (Humaidan, 1980).

Table 3.8 Present consumed irrigation water and estimated irrigation requirements for Al-Hasa Irrigation Project

	Water Consumtion [million cubic meters/year]			Project efficiency	Field application efficiency	Combined operation-conveyaance efficiency
	Winter	Summer	Total	Ep	Ea	EoEc
	Present Consumption					
	174[a] (53%)	154[a] (47%)	328[a] (100%)	39%	0.55[b]	0.70
	Project irrigation requirements					
Present cultivated areas						
-dates	22	49.3				
-alfalfa	12	24.5				
-vegetables	7	14.0				
	41	87.8	128.8	100%		
For the new areas (4438 ha)	19	54.7	74	100%		
For the total project area (11534 ha)	60	142.5	202.8	100%		

[a]Personal communication with HIDA (1985)
[b]Measured efficiency
Source: (Abderrahman, 1988)

TABLE 3.9 Cultivated areas in the Al-Hasa Project [ha][a]

Total area	Total cultivated area	Uncultivated area (arable)	Date palm area	Alfalfa area	Vegetables area
11534	7096 100%	4438	6599[b] (93%)[e]	1348[c] (19%)[e]	1064[d] (15%)[e]

[a]From HIDRA (1980)
[b]This area includes about 1915 ha of mixed cultivation with alfalfa and/or vegetables
[c]1348 ha are equal to 1048 ha cultivated between date palm trees plus 300 ha cultivated in open fields
[d]1064 ha are equal to 867 ha cultivated between date palm trees plus 197 ha cultivated in open areas
[e]Percentage of the total cultivated area

Source: (Abderrahman, 1988)

TABLE 3.10	Cropping pattern in Al-Hasa during the 1971/72 crop year			
		Area	*Production*	*Yield*
Crop	[Donums]*	% of Total	[Tons]	[Tons/ha]
Date Palm	41,210	69.75	46,751	11.35
Pomegranates	1,911	3.23	4,506	23.58
Other Fruits	894	1.51	2,067	23.12
Tomatoes	1,038	1.76	1,937	18.66
Dry Onions	510	0.86	518	10.16
Okra	144	0.24	100	6.94
Watermelons	127	0.21	333	26.22
Egg Plant	122	0.20	265	21.72
Radishes	121	0.20	119	9.83
Squash	115	0.19	147	12.78
Pumpkins	88	0.15	163	18.52
Green Onions	76	0.13	66	8.68
Lettuce	73	0.12	274	37.53
Cucumbers	72	0.12	151	20.97
Other Vegetables	144	0.24	222	15.42
Alfalfa**	11,336	19.19	93,593	82.56
Other Fodder Crops	125	0.21	-	-
Rice	498	0.84	72	1.45
Wheat	300	0.51	45	1.50
Barley	174	0.29	29	1.67
Total	59,078	100.00		

*10 Donums = 1 ha

**Mostly grown under date palms

Source: (Statistics Unit, Ministry of Agriculture and Water

The importance of dates in the economy has diminished to a pronounced level during the last twenty years. It looks as if the present economic conditions at Al-Hasa do not favor the cultivation of date palms. Most of these trees are not generating enough income to justify their eternity. The reasons behind this include a constant decline in dates consumption, increased production costs versus stationary output prices, plus easier and more attractive opportunities in sectors other than agriculture - especially in oil industry.

Although vegetables occupied only about 263 ha in 1971-1972 (Table 3.10), farmers are recently switching to a wide range of vegetables, because of their relatively high return. Vegetables are generally grown in small plots in open fields, or under palm trees - whenever spacing allows. However, the problem in cropping vegetables is connected to water availability. The system of irrigation permits farmers to take any water quantity as far as there is water in irrigation canals, but not whenever their vegetables need.

Alfalfa is a perennial crop planted throughout the Oasis, mainly under date palms. Twelve cuttings are usually obtained per year, each one yielding about 10 tons per hectare in open field and approximately 5 hectares when the crop is planted under date palms. Alfalfa is used to feed domesticated animals or sold as a green fodder in the market (Labban, 1974).

Chapter 4

MATHEMATICAL FORMULATION OF THE PROBLEM

4. 1 Introduction

Groundwater modeling begins with the understanding of the physics of the problem under investigation. Cause-effect relationships are determined and a *conceptual model* of how the components of the problem operate is formulated.

The physical nature of the problem should then be transformed into a set of governing differential equations that relates the unknown parameters of interest with the boundary and initial conditions. This constitutes the *mathematical model.* Such a model involves mass and momentum conservations that describe continuous variables (for instance, total head) over the region of interest.

Solution of the governing differential equations means finding the unknown variable at various locations and time horizon within the aquifer. For most of the problems, the solution of governing differential equations is not feasible analytically. Thus, simplifying assumptions (like assuming : infinite aquifer, radial flow, among other assumptions) should be made to get simpler subset of the original equations. The equations and solutions of this subset are called *analytical models.* Jacob-Cooper straight line and Theis type curve represent solutions of one such analytical model (Mercer and Faust, 1980b).

In fact, the classical analytical techniques of differentiation and integration will yield big complications if the real nature of any aquifer is to be accounted for. Terms like anisotropy and/or heterogeneity are more than enough to make even small aquifer unsolvable analytically. Thus, alternative solution methods have been used to overcome this limitation. The most widely used alternative to analytical method is the numerical method. In such methods, continuous variables are replaced with discrete variables that are defined at finite number of nodes (or grid blocks). Consequently, this transforms the original continuous differential equations (that express the hydraulic head at every point in the aquifer) into a finite number of algebraic equations that defines hydraulic head at specific points. This process constitutes a *numerical model.* Figure 4.1 clarifies the relationship between the conceptual model, the mathematical model, the analytical model, and the numerical model.

4. 2 Groundwater Flow Equation

Groundwater flow equation forms a mathematical model. Fundamental equations used in general groundwater applications are derived on the basis of three conservation principles: Conservation of Mass, Conservation of Momentum (Darcy's Law) and Conservation of Energy. Conservation principles reflect the fact that the net system

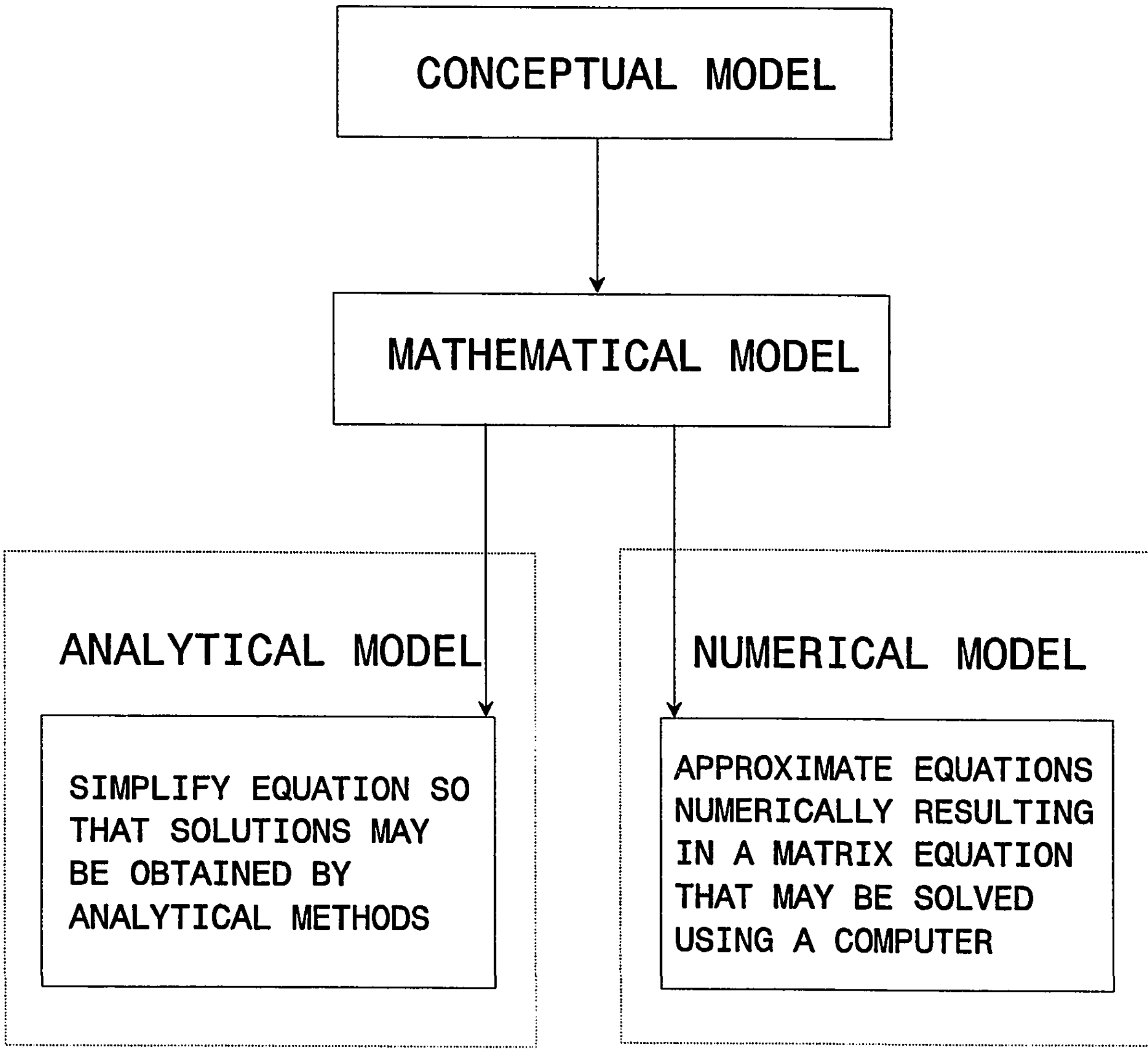


Figure 4.1 Logic diagram for developing a mathematical model (After Mercer and Faust, 1980a)

property (mass, momentum or energy in the aquifer) entering or leaving any volume of the system (here, the system is a groundwater aquifer) during some time interval is equal to the change of that property in the considered volume. The result of derivation is the general governing partial differential equation(s). Figure 4.2 is a diagram of the major components of the groundwater flow equation. The following is a compact, yet not rigorous, derivation of the general groundwater flow equation.

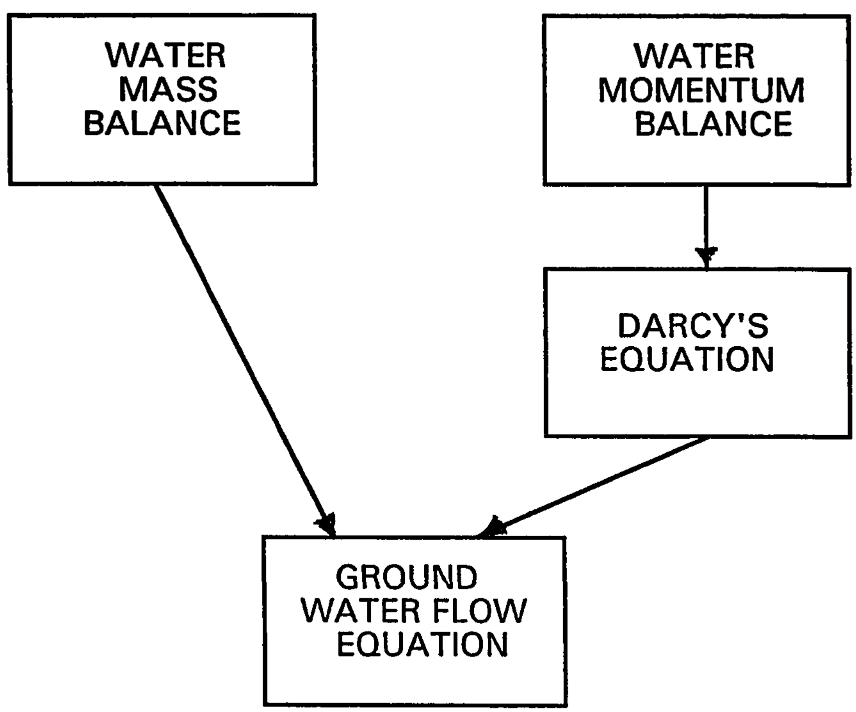


Figure 4.2: Diagram of the major components of the groundwater flow equation.

4. 2. 1 Conservation of Mass (Mass Balance)

The mass balance is determined by considering changes in mass of a small elemental volume of porous media over a small time interval (Δt). Figure 4.3 shows a representative elemental volume (REV) with a recharge/discharge term W. For mass balance :

mass outflow rate - mass inflow rate
= time rate of mass storage
within the control volume (4.1)

Using the quantities in Figure 4.3, equation (4.1) gives :

$$(\rho\, Q)_{i+\Delta i} - (\rho\, Q)_i = \Delta i \frac{\partial}{\partial i}(\rho\, Q)_i \tag{4.2}$$

Where:

ρ = density $[M/L^3]$

Q = Volumetric flowrate $[L^3/T]$

i = Any of the principal directions x, y, or z

The volumetric flowrate Q in any direction i can be written as :

$$Q_i = q_i A_i \tag{4.3}$$

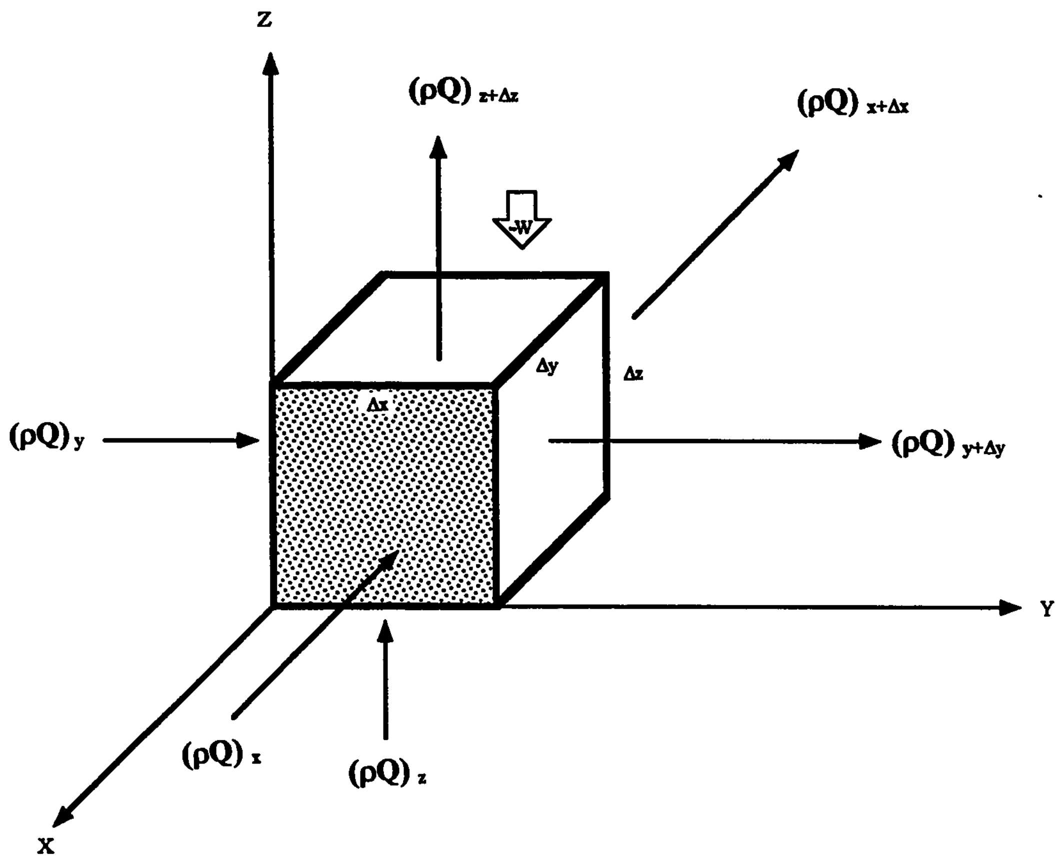


Figure 4.3 Elemental Volume of Porous Material Showing Flow Across All Faces (After Mercer & Faust, 1980b)

Where:

$q_i =$ Specific discharge (Darcy's velocity) or discharge per unit area $[\,L/T\,]$

$A_i =$ Cross-sectional area perpendicular to direction i $[\,L^2\,]$

Substituting equation (4.3) into equation (4.2), one obtains :

$$(\,Outflow\ rate\ -\ Inflow\ rate\,)_i = \frac{\partial}{\partial i}(\,\rho\, q_i)\,\Delta V \tag{4.4}$$

Where:

$\Delta V =$ Volume of the representative element

$= \Delta x\,\Delta y\,\Delta z \quad [\,L^3\,]$

Replacement of i with x, y, and z (the principal directions) in equation (4.4), yields three equations :

$$(\,Outflow\ rate\ -\ Inflow\ rate\,)_x = \frac{\partial}{\partial x}(\,\rho\, q_x)\,\Delta V \tag{4.4a}$$

$$(\,Outflow\ rate\ -\ Inflow\ rate\,)_y = \frac{\partial}{\partial y}(\,\rho\, q_y)\,\Delta V \tag{4.4b}$$

$$(\,Outflow\ rate\ -\ inflow\ rate\,)_z = \frac{\partial}{\partial z}(\,\rho\, q_z)\,\Delta V \tag{4.4c}$$

Now, using equations (4.4a), (4.4b), and (4.4c) in equation (4.1) gives :

$$\left(\frac{\partial}{\partial x}(\rho\, q_x)+\frac{\partial}{\partial y}(\rho\, q_y)+\frac{\partial}{\partial z}(\rho\, q_z)\right)\Delta V = -\frac{\partial M}{\partial t} \tag{4.5}$$

Where:

$M =$ Initial mass in the elemental volume $[\,M\,]$

$t =$ time $[\,T\,]$

$-\dfrac{\partial M}{\partial t}$: indicates increase or decrease in mass (depending on whether the outflow is > inflow or outflow is < inflow) $[\,M/T\,]$

The next step is to evaluate each of the terms $\frac{\partial}{\partial i}(\rho\, q_i)$. Applying ordinary rules of differentiation, the following is obtained :

$$\frac{\partial}{\partial i}(\rho\, q_i) = \frac{\partial \rho}{\partial i}q_i+\rho\frac{\partial q_i}{\partial i} \tag{4.6}$$

Assuming *incompressible* fluid (i.e ρ *is constant*) the first term in the right-hand side of equation (4.6) vanishes (because the derivative of a constant is zero). Hence :

$$\frac{\partial}{\partial i}(\rho\, q_i) = \rho\frac{\partial q_i}{\partial i} \tag{4.7}$$

Upon replacement of index i by x, y, and z respectively in equation (4.7), and substituting the resulting terms into equation (4.5), the following is obtained :

$$\rho\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)\Delta V = -\frac{\partial M}{\partial t} \tag{4.8}$$

Rewriting equation (4.8) with a recharge (or discharge) term gives :

$$\rho\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}+W\right)\Delta V = -\frac{\partial M}{\partial t} \tag{4.9}$$

Where :

$W =$ Sink or source function. It is equal to the Volume of water injected into or out of the aquifer per unit volume of the aquifer per unit time $[1/T]$

4. 2. 2 Conservation of Momentum (Darcy's Law)

The most general form of Darcy's law can be expressed in vector as well as in tensor notation. The following is the *tensor* (also called *summation* or *index)* form :

$$q_i = -K_{ij}\frac{\partial h}{\partial j} \tag{4.10}$$

Where :

$K =$ Hydraulic conductivity tensor $[L/T]$

$h =$ Hydraulic head $[L]$

For any i (which will be x or y or z), the summation is over j (i.e j will take the values x, y, and z respectively). The hydraulic conductivity tensor K_{ij} has nine components to describe its effects in all directions. But, assuming that it is symmetric and that the principal components K_{xx}, K_{yy}, K_{zz} are oriented along the x-, y- and z-directions respectively, Darcy's equation may be rewritten in the following *differential form* :

$$q_x = -K_{xx}\frac{\partial h}{\partial x} \tag{4.10a}$$

$$q_y = -K_{yy}\frac{\partial h}{\partial y} \tag{4.10b}$$

$$q_z = -K_{zz}\frac{\partial h}{\partial z} \tag{4.10c}$$

Where :

$x, y, z =$ Cartesian (rectangular) coordinate axes

$\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}, \frac{\partial h}{\partial z} =$ Components of hydraulic head gradient in the x-, y- and z-directions

The minus sign in Darcy's law indicates that the flow is in the direction of decreasing head. Back substitution of equations (4.10a), (4.10b), and (4.10c) into equation (4.9) and dividing throughout by $\rho \Delta V$ yields :

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = \frac{1}{\rho \Delta V}\frac{\partial M}{\partial t} \quad (4.11)$$

Following Davis and DeWiest (1966) - among others :

$$\frac{\partial M}{\Delta V} = \rho\,(\alpha + n\,\beta)\,\partial p \quad (4.12a)$$

and

$$\partial p = \rho\, g\, \partial h \quad (4.12b)$$

Where :

$\alpha =$ Compressibility of the porous medium $[\, m^2/N \equiv Pa^{-1}\,]$

$n =$ Porosity of the porous medium $[\, dimensionless \,]$

$\beta =$ Compressibility of water $[\, m^2/N \equiv Pa^{-1}\,]$

$p =$ Pore-water pressure $[\, N/m^2 \equiv Pa\,]$

Thus, substituting equations (4.12a) and (4.12b) in equation (4.11) gives :

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W$$

$$= \rho\, g\,(\alpha + n\,\beta)\frac{\partial h}{\partial t} \quad (4.13)$$

By definition, the *specific storage* S_s is the volume of water released from storage per unit volume of aquifer per unit decline in head $[L^{-1}]$. It is not difficult to show that the specific storage of the aquifer S_s can be written as :

$$S_s = \rho g (\alpha + n \beta) \tag{4.14}$$

Utilizing the value of S_s, equation (4.13) becomes :

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s \frac{\partial h}{\partial t} \tag{4.15}$$

Equation (4.15) is a general (yet not the most general) form of the groundwater flow equation. It could be more general if the assumption of incompressible fluid is released, and if Darcy's law is used in its most general form (i.e allowing the hydraulic conductivity tensor to take its nine components). However, in a wide category of groundwater problems, the release of the simplifying assumptions associated with equation (4.15) and the use of the most general form are not really warranted.

Equation (4.15) is the unsteady or *transient*, three-dimensional groundwater flow model. Sometimes it is called the *diffusion equation.* Mathematically, it is classified as a *parabolic* partial differential equation.

4. 3 Formulation of the Problem

Detailed development of every term in the general groundwater flow equation can be found in textbooks (e.g. Bear, 1972, McWhorter and Sunada, 1977) and in some published papers (e.g. Mercer and Faust, 1980b). Physically, the first three terms at the left-hand side of equation (4.15) are the net difference in water rate entering or leaving a specified control volume. W is the rate of gained (or lost) water from some source (or sink) within the volume or along any one of its boundaries. The right-hand side is the rate change of stored water in the volume.

The present study will utilize a quasi three-dimensional equation describing an unsteady groundwater flow in a heterogeneous isotropic leaky confined aquifer. The following simplifying assumptions will be used in writing it (Mercer and Faust, 1980b) :

(1) porous media

(2) Darcy's law applies

(3) incompressible fluid

(4) negligible vertical variations in properties and head

(5) single aquifer with areal, confined flow

(6) the aquifer vertical compressibility is linearly elastic

(7) directions of anisotropy line up with the coordinate system (that is, the principal components of transmissivity tensor are co-linear with the rectangular

system).

(8) leakage through the confining bed into the aquifer is vertical and proportional to the difference in the head between the aquifer and the head in an overlying or underlying source aquifer

(9) the head in the source aquifer is constant with time

(10) the storage in the confining bed is negligible

(11) the aquifer head does not fall below the bottom of the confining layer.

It is worthy noting that the recharge function W in equation (4.15) can include well discharge, induced infiltration, steady and/or unsteady (transient) leakage from confining layers, recharge from precipitation, and evapotranspiration (Mercer and Faust, 1980b). And With reference to equation equation (4.15), that has been derived in the previous section, the needed equation for this study is easily obtained via integration of equation (4.15) over the saturated thickness. The integration will yield new terms like *transmissivity* (T), and *Storativity* (S), which is also known as *storage coefficient*.

Transmissivity is the multiplication product of the hydraulic conductivity (K) and the saturated thickness (b). That is,

$$T = K \cdot b \tag{4.16}$$

It represents the discharge from an aquifer area of unit width throughout the total depth (b). This definition explains the use of units like ((cubic meter/day) per meter width) or ((gallon/ day) per feet width) that are utilized by the water industry people.

On the other hand, storativity (or storage coefficient) results from the multiplication of the specific storage with the saturated thickness. In mathematical language,

$$S = b \cdot S_s \tag{4.17}$$

Substituting the value of S_s, equation (4.14), into equation (4.17), the coefficient of storage can be related to both water and porous media properties of the aquifer :

$$S = b \rho g (\alpha + n \beta) \tag{4.18}$$

Upon expansion, equation (4.18) becomes :

$$S = \rho g b \alpha + \rho g b n \beta \tag{4.19}$$

The first term in equation (4.19) is the contribution due to porous media compressibility, while the second expression is due to water expansion in the aquifer.

Utilizing the above concepts of transmissivity and storativity, and incorporating equations (4.16) and (4.17), equation (4.15) can, now, be rewritten for *leaky confined* aquifer :

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)+W' - \frac{K'}{b'}(h - h') = S\frac{\partial h}{\partial t} \qquad (4.20)$$

Where:

T_{xx} = Transmissivity in the x-direction $[L^2/T]$

T_{yy} = Transmissivity in the y-direction $[L^2/T]$

h = Hydraulic head $[L]$

W' = Remaining source terms (other than those included in the recharge function (W), which appeared in equation (4.15)) $[1/T]$

S = Storage coefficient or storativity $[\mathit{dimensionless}]$

K' = Hydraulic conductivity of the confining bed $[L/T]$

b' = Thickness of the confining bed $[L]$

h' = Hydraulic head in the source aquifer $[L]$

t = Time $[T]$

x, y, z = Cartesian (rectangular) coordinate axes $[L]$

More details regarding this equation and its accompanying assumptions are given by Pinder and Bredehoeft (1968), Mercer and Faust (1980b), and Pinder and Gray (1977).

The study area will be modeled as part of a *multi-layered aquifer aquitard system.* The existence of such a system is based on the following considerations (Rasheeduddin, 1988) :

(1) earlier studies done by different researchers considering water-level data, pumping tests, water temperature, hydrochemistry and isotope analysis (Naimi (1965), Italconsult (1969), BRGM (1977), Leichtweiss-Team (1979), GDC (1980))

(2) the intervening aquitard layers are leaky

(3) flow to or from adjacent aquifers takes place under existing vertical gradients

(4) changes in vertical flow rates between aquifers would be induced by head changes in the aquifer system as a response to changes in pumping pattern.

The above considerations require that equation (4.20) be rewritten to reflect the use of a multi-layered system. For isotropic conditions with no recharge, equation (4.20) becomes (Bear, 1979):

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+\frac{h_{k+1}-h_k}{\sigma^{l}}+\frac{h_{k-1}-h_k}{\sigma^{u}}$$

$$= S\,\frac{\partial h_k}{\partial t} + q(x, y, t) \tag{4.21}$$

Where:

$T =$ Transmissivity $[L^2/T]$

$h_k =$ Hydraulic head in aquifer k $[L]$

$q(x, y, t) =$ Water sinks term per unit area $[L/T]$

$S =$ Storage coefficient or storativity [*dimensionless*]

$t =$ Time [T]

$x, y, z =$ Cartesian (rectangular) coordinate axes [L]

$\sigma^{l} =$ Leakage coefficient of the lower aquitard [T]

$\sigma^{u} =$ Leakage coefficient of the upper aquitard [T]

The *leakage coefficient* measures the aquitard resistance to leak flow from its semi-pervious layers. Hantush (1949, 1964) gave the following expression for it :

$$\sigma = \frac{b'}{K'} \tag{4.22}$$

Where :

$K' =$ Hydraulic conductivity of the confining bed [L/T]

$b' =$ Thickness of the confining bed [L]

Equation (4.21) should be accompanied by proper definition of the boundary and initial conditions (BC's and IC's) of flow and/or head conditions that pertain to the problem under consideration. Having done that, the equation and all the specified boundaries will formulate a mathematical model that governs the groundwater flow in the study area. The analytical solution of such a *boundary value problem (BVP)* is tedious, except for some simple situations. In the coming chapter, the famous finite difference numerical technique will be used in the solution of the present research problem.

In this study, horizontal flow will be simulated in aquifer units. On the other hand, vertical flow will be treated in the aquitards by assigning convenient vertical hydraulic conductivities to the various aquitard units. This simplification is justified by Bredehoeft and Pinder (1970) whenever aquifers conductivities are hundred times more than those of the aquitards. And, to avoid having nodes within them, aquitard units will be assumed to have no storativity (McDonald and Harbough, 1984).

Chapter 5

NUMERICAL MODELING OF THE PROBLEM

5. 1 Introduction

A model is a tool designed to represent a simplified version of reality. So, groundwater models are, also, representation of reality and, if properly constructed, can be valuable tools in analyzing many groundwater problems.

The goal of modeling is to find the value of the unknown variable (variables) at every point in the domain under investigation. Hence, once the mathematical model is constructed, the next step is to solve the governing equations either by numerical technique or by analytical methods.

Simplifying assumptions must, always, be made in order to construct a model because field conditions are too complicated to be simulated exactly. Usually, the assumptions needed for analytical solution are fairly restrictive and, for many problems, are not realistic (e.g. requirement of homogeneous and isotropic medium). Such restrictive assumptions are not required by numerical techniques.

Although the birth of groundwater hydrology as a quantitative science can be traced to the year 1856 (Wang and Anderson 1982), numerical methods have been in use, effectively, since the late of

1960s. Their initial advancements were very slow due to computer limitations at that time. But, with the rapid developments in computer speed and storage capacity, numerical techniques (like finite difference and finite element methods) also proceed very quickly. Such techniques were used in solving many groundwater problems of diversified nature.

5. 2 An Overview of Finite Difference Method

5. 2. 1 General

Numerical method begins with discretizing the region described by the set of partial differential equations into a *grid.* The governing partial differential equations are, then, approximated in time and space by a set of algebraic equations. These discrete algebraic equations can be put into matrix form, and various matrix solution techniques -direct and iterative methods- are applied to get the unknown values.

Generally, in groundwater flow problems, the left-hand side of a matrix equation contains a coefficient matrix multiplied by a vector matrix of the unknowns. The coefficient matrix stores values related to grid spacing and aquifer properties (hydraulic conductivity, for example). The unknown vector matrix contains dependent variables to be determined (head at each node, for instance). The right-hand side of the matrix equation is a vector matrix of all known data such as pumping rates and boundary head values.

Numerically, direct and iterative schemes are the two broad methods used to solve a matrix equation. In *direct* approach, a series of operations is performed only once, with no initial guesses, providing an exact solution plus and/or minus computer round-off error. On the other hand, *iterative methods* involve making initial guess for the unknown and, then, improving this guess iteratively until a prespecified error tolerance limit is reached.

The decision as which of these methods to be used is problem dependent. In general, for large problems, direct techniques may turn to be inefficient in terms of storage and computing time _ and, thus, iterative approaches are preferred. Unfortunately, iterative scheme can not work well (can not converge) with ill-conditioned matrices. An example of an ill-conditioned matrix is one in which main diagonal terms are much smaller than other terms in the matrix. The relative merits of direct and iterative methods are discussed in Faust and Mercer (1980c).

The major and most popular numerical techniques used in groundwater flow problems are finite difference (FD) and finite element (FE) methods. Figure 5.1 shows components and steps involved in model development for both of these two famous methods. In the present study, finite difference approach will be used. And as such, a compact mathematical treatment will be furnished for some of the basic expressions used in this method.

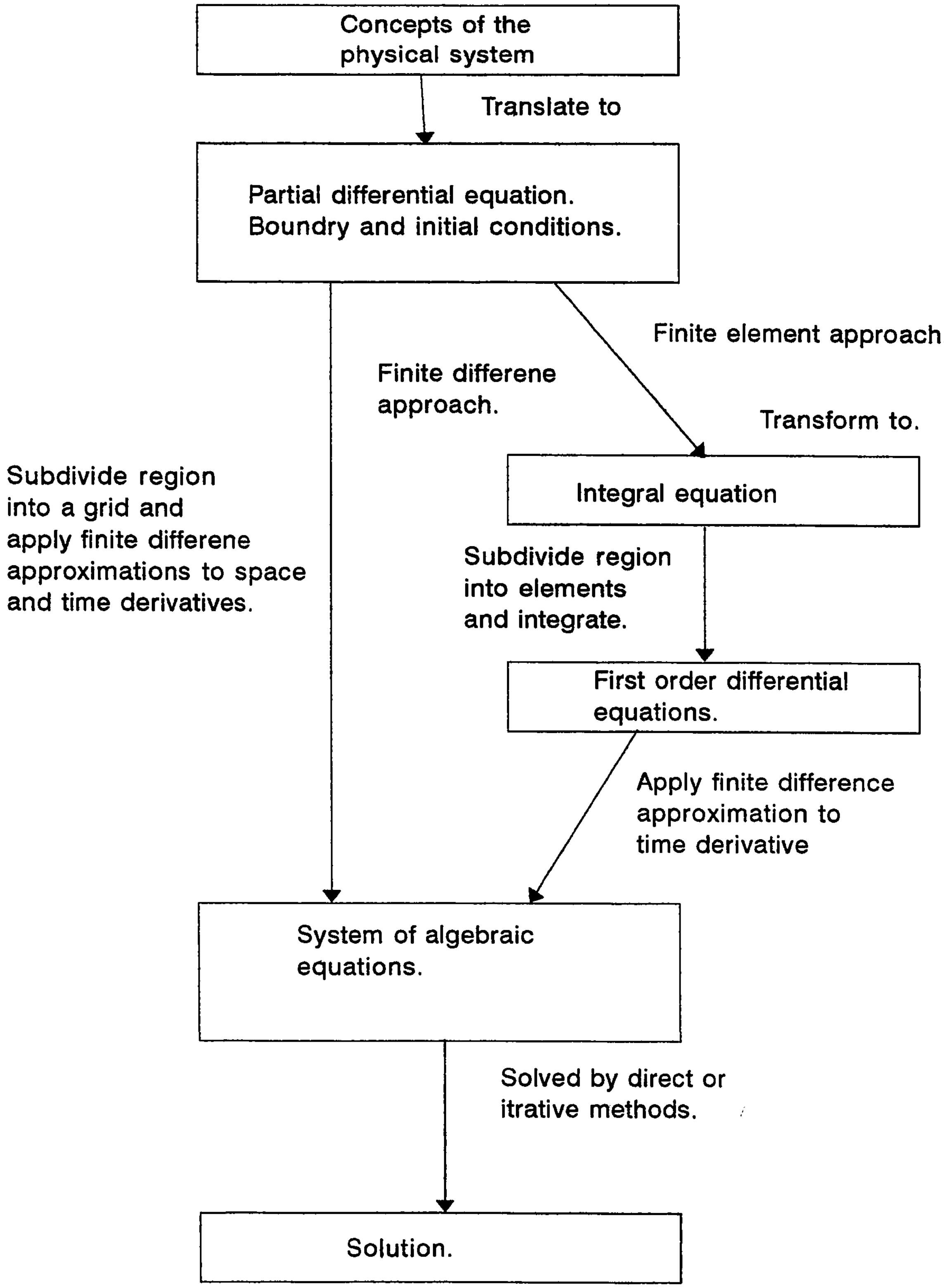


Figure 5.1 Generalized Model Development by Finite Difference and Finite Element Methods (After Faust & Mercer, 1980c)

5. 2. 2 Finite Difference Method (FDM)

General

Probably, this method is the oldest, most popular and conceptually easiest of all numerical techniques. It discretizes the problem area into rectangular *cells* that are characterized by their *nodes*. The set of all cells and their corresponding nodes constitute a *grid* that could be either *block-centered* or *mesh-centered*. In the block-centered grid, the nodes are centered between grid lines, whereas in the mesh-centered grid the nodes are the intersection points of the grid lines. The choice of the grid type is problem dependent and mostly dominated by the boundary conditions. The most popular grids are the rectangular ones. They can be either *regular* (that is, they have the same spacing in both x- and y-directions) or *irregular*.

Finite difference method, then, approximates the partial differential equations governing the groundwater flow in the simulation domain by a *truncated Taylor Series* at each node. Usually the series is truncated after first or second derivatives (i.e. first or second order terms). But, regardless of the order term degree, this will result in an algebraic equation for each node. The algebraic equation for any node shows the contribution of adjacent nodes to that particular node. This will result in a set of algebraic equations that replaces the original partial differential equations. For N nodes, there will be N equations with N unknown values (head values in most groundwater flow problems). These N equations may be put in a matrix form and solved by suitable matrix solution methods.

Finite Diffrence Expression for the First and the Second Derivatives

In this study, the finite difference technique will be used. Utilizing this numerical method dictates expressing derivatives of the head function in terms of the head function itself. This is required in transforming the governing partial differential equation(s) into a set of of algebraic one(s). In such a process, one needs discrete algebraic expressions of the first and second partial derivatives. Higher order derivatives do not show up in equation (4.21) and, thus, no algebraic expressions will be developed for them.

Figure 5.2 is a finite set of points on a regularly spaced grid. Each point represents a node. The horizontal spacing between the nodes is Δx and the vertical spacing is Δy. To locate any point in the grid, an integer pair (i, j) is specified. The value of the head at node (i,j) is $h_{i,j}$. Assuming that the head function in the aquifer fulfills the mathematical requirement of Taylor's Series expansion, the head values at nodes (i+1,j) and (i-1,j) can be written in terms of the head function and its derivative at the adjacent node (i,j) :

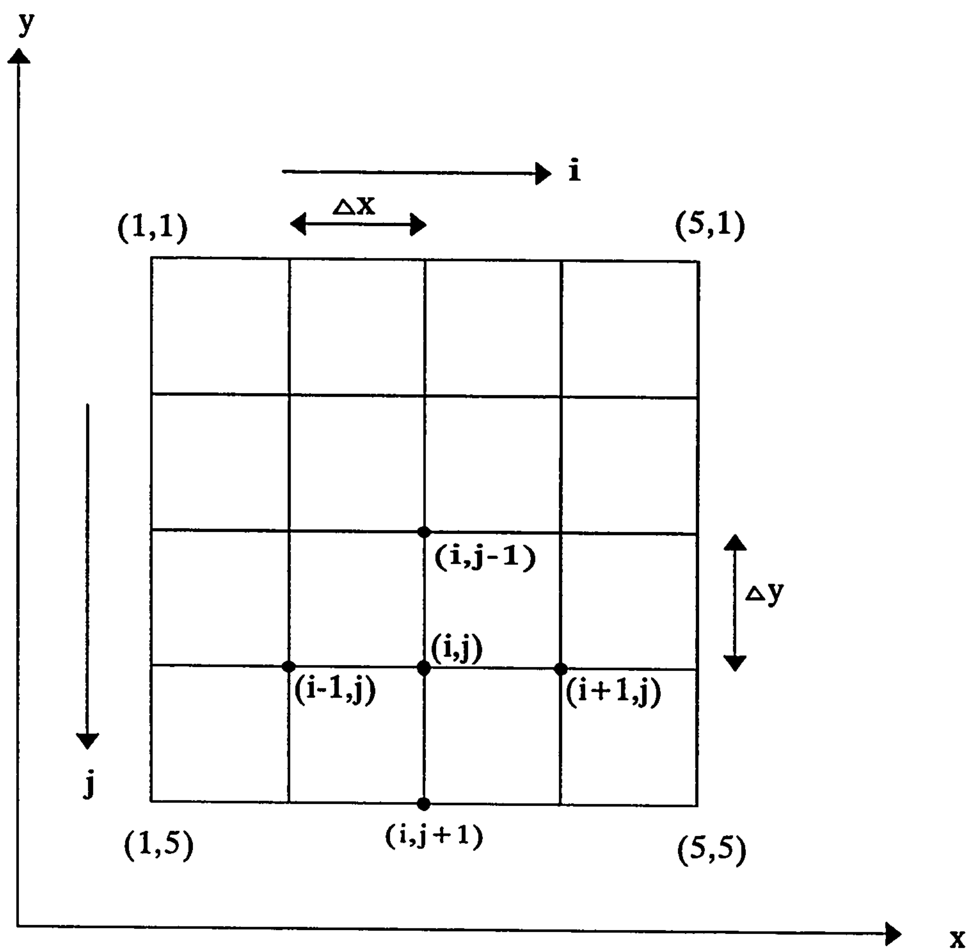


Figure 5.2 Finite difference grid showing index numbering convention (After Wang and Anderson, 1982)

$$h_{i+1,j} = h_{i,j} + \Delta x \left.\frac{\partial h}{\partial x}\right|_{i,j} + \frac{(\Delta x)^2}{2!} \left.\frac{\partial^2 h}{\partial x^2}\right|_{i,j}$$

$$+ \left.\frac{\partial^3 h}{\partial x^3}\right|_{i,j} \frac{(\Delta x)^3}{3!} + \dots \qquad (5.1)$$

$$h_{i-1,j} = h_{i,j} + (-\Delta x) \left.\frac{\partial h}{\partial x}\right|_{i,j} + \frac{(-\Delta x)^2}{2!} \left.\frac{\partial^2 h}{\partial x^2}\right|_{i,j}$$

$$+ \frac{(-\Delta x)^3}{3!} \left.\frac{\partial^3 h}{\partial x^3}\right|_{i,j} + \dots \qquad (5.2)$$

Subtracting equation (5.2) from equation (5.1) yields :

$$h_{i+1,j} - h_{i-1,j} = 2(\Delta x) \left.\frac{\partial h}{\partial x}\right|_{i,j}$$

$$+ 2 \frac{(\Delta x)^3}{3!} \left.\frac{\partial^3 h}{\partial x^3}\right|_{i,j} + \dots \qquad (5.3)$$

After some algebra, and terminating terms after the third-rank derivative, the first derivative is obtained :

$$\left.\frac{\partial h}{\partial x}\right|_{i,j} = \frac{1}{2(\Delta x)} \left(h_{i+1,j} - h_{i-1,j} \right)$$

$$- \frac{(\Delta x)^2}{3!} \left.\frac{\partial^3 h}{\partial x^3}\right|_{i,j} \qquad (5.4)$$

The last term in equation (5.4) is said to be of *order* $(\Delta x)^2$. Symbolically, this is written as $O(\Delta x)^2$. In fact, this term represents the amount of error committed due to *truncation*. If this is kept in mind, equation (5.4) can now be rewritten as :

$$\left.\frac{\partial h}{\partial x}\right|_{i,j} = \frac{1}{2(\Delta x)}\left(h_{i+1,j} - h_{i-1,j}\right) \tag{5.5}$$

Adding equtions (5.1) and (5.2) results in :

$$h_{i+1,j} + h_{i-1,j} = 2\,h_{i,j} + 2\,\frac{(\Delta x)^2}{2!}\left.\frac{\partial^2 h}{\partial x^2}\right|_{i,j} + 2\,\frac{(\Delta x)^4}{4!}\left.\frac{\partial^4 h}{\partial x^4}\right|_{i,j} + \ldots \tag{5.6}$$

With some algebraic manipulationin, and by terminating the high order derivatives, an expression for the second derivative is found :

$$\left.\frac{\partial^2 h}{\partial x^2}\right|_{i,j} = \frac{1}{(\Delta x)^2}\left(h_{i+1,j} + h_{i-1,j}\right) - \frac{2}{(\Delta x)^2}\,h_{i,j} - \frac{2}{(\Delta x)^2}\,\frac{(\Delta x)^4}{4!}\left.\frac{\partial^4 h}{\partial x^4}\right|_{i,j} \tag{5.7}$$

As in equation (5.5), the last term represents an error of *order* $(\Delta x)^2$. Taking this into account, if any further calcultions warrent that, equation (5.7) can be written in the following form :

$$\left.\frac{\partial^2 h}{\partial x^2}\right|_{i,j} = \frac{1}{(\Delta x)^2}\left(h_{i+1,j} + h_{i-1,j} - 2h_{i,j}\right) \tag{5.8}$$

The same methodology can be applied to express the head values in the vertical direction; that is to say: applying Taylor's Series expansion, the head values at nodes (i,j+1) and (i,j-1) are readily obtained in terms of the head function and its derivatives at the adjacent node (i,j). What is needed is a to replace increments in the x-direction (i.e i-direction) in all of the equations by increments in the y-direction (i.e j-direction). Having done so, the following equtions can be written :

$$h_{i,j+1} = h_{i,j} + \Delta y \left.\frac{\partial h}{\partial y}\right|_{i,j} + \frac{(\Delta y)^2}{2!}\left.\frac{\partial^2 h}{\partial y^2}\right|_{i,j} + \frac{(\Delta y)^3}{3!}\left.\frac{\partial^3 h}{\partial y^3}\right|_{i,j} + \ldots \tag{5.9}$$

$$h_{i,j-1} = h_{i,j} + (-\Delta y)\left.\frac{\partial h}{\partial y}\right|_{i,j} + \frac{(-\Delta y)^2}{2!}\left.\frac{\partial^2 h}{\partial y^2}\right|_{i,j} + \frac{(-\Delta y)^3}{3!}\left.\frac{\partial^3 h}{\partial y^3}\right|_{i,j} + \ldots \tag{5.10}$$

Subtracting equation (5.10) from equation (5.9) yields :

$$h_{i,j+1} - h_{i,j-1} = 2(\Delta y) \left.\frac{\partial h}{\partial y}\right|_{i,j} + 2\frac{(\Delta y)^3}{3!} \left.\frac{\partial^3 h}{\partial y^3}\right|_{i,j} + \dots \tag{5.11}$$

Terminating terms after the third-rank derivative, and solving for the first derivative :

$$\left.\frac{\partial h}{\partial y}\right|_{i,j} = \frac{1}{2(\Delta y)} (h_{i,j+1} - h_{i,j-1}) - \frac{(\Delta y)^2}{3!} \left.\frac{\partial^3 h}{\partial y^3}\right|_{i,j} \tag{5.12}$$

As was the case in equation (5.4), the last term in equation (5.12) is said to be of *order* $(\Delta y)^2$. Symbolically, this is written as $O(\Delta y)^2$ This term represents the amount of error resulted from *truncation* of higher order derivatives. If this is kept in mind, equation (5.12) can now be rewritten as :

$$\left.\frac{\partial h}{\partial y}\right|_{i,j} = \frac{1}{2(\Delta y)} (h_{i,j+1} - h_{i,j-1}) \tag{5.13}$$

Expression for the second derivative of the head can be reached via adding equtions (5.9) and (5.10) :

$$h_{i,j+1} + h_{i,j-1} = 2\, h_{i,j} + 2\, \frac{(\Delta y)^2}{2!}\, \frac{\partial^2 h}{\partial y^2}\bigg|_{i,j} + 2\, \frac{(\Delta y)^4}{4!}\, \frac{\partial^4 h}{\partial y^4}\bigg|_{i,j} + \ldots \tag{5.14}$$

With some algebraic manipulationin, and by terminating the high order derivatives, the second derivative is found :

$$\frac{\partial^2 h}{\partial y^2}\bigg|_{i,j} = \frac{1}{(\Delta y)^2}\left(h_{i,j+1} + h_{i,j-1}\right) - \frac{2}{(\Delta y)^2} h_{i,j} - \frac{2}{(\Delta y)^2}\, \frac{(\Delta y)^4}{4!}\, \frac{\partial^4 h}{\partial y^4}\bigg|_{i,j} \tag{5.15}$$

The error term is of *order* $(\Delta y)^2$. Keeping this in mind, equation (5.7) can be written in the following form :

$$\frac{\partial^2 h}{\partial y^2}\bigg|_{i,j} = \frac{1}{(\Delta y)^2}\left(h_{i,j+1} + h_{i,j-1} - 2h_{i,j}\right) \tag{5.16}$$

The coming section will show how the above derived expressions of the first and second derivatives are utilized in writing the governing flow equation in a discrete form.

Finite Diffrence Formulation

In chapter 4, the governing equation of the groundwater flow pertaining to the present study was found to be :

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+W' - \frac{K'}{b'}(h - h')$$

$$= S\frac{\partial h}{\partial t} \qquad (4.20)$$

Where:

$T =$ Transmissivity $[L^2/T]$

$h =$ Hydraulic head $[L]$

$W' =$ Remaining source terms (other than those included in the recharge function (W), which appeared in equation (4.15)) $[1/T]$

$S =$ Storage coefficient or storativity [*dimensionless*]

$K' =$ Hydraulic conductivity of the confining bed $[L/T]$

$b' =$ Thickness of the confining bed $[L]$

$h' =$ Hydraulic head in the source aquifer $[L]$

$t =$ Time $[T]$

$x, y, z =$ Cartesian (rectangular) coordinate axes $[L]$

And, with the use of a multi-layered aqufer-aquitard system, equation (4.20) was rewritten as :

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+\frac{h_{k+1}-h_k}{\sigma^l}+\frac{h_{k-1}-h_k}{\sigma^u}$$

$$= S\frac{\partial h_k}{\partial t}+q\,(x,y,t) \qquad (4.21)$$

Where:

$T =$ Transmissivity $[L^2/T]$

$h_k =$ Hydraulic head in aquifer k $[L]$

$q\,(x,y,t) =$ Water sources or sinks term per unit area $[L/T]$

$S =$ Storage coefficient or storativity [*dimensionless*]

$t =$ Time $[T]$

$x, y, z =$ Cartesian (rectangular) coordinate axes $[L]$

$\sigma^l =$ Leakage coefficient of the lower aquitard $[T]$

$\sigma^u =$ Leakage coefficient of the upper aquitard $[T]$

For the finite difference formulation, each of the above equations requires that $\frac{\partial h}{\partial x}$, $\frac{\partial^2 h}{\partial x^2}$, $\frac{\partial h}{\partial y}$, $\frac{\partial^2 h}{\partial y^2}$ be expressed with their finite difference equivalents. A further modification will be the use of a *block-centered* nodes instead of the previous grid-centered one. Figure 5.3 is a block-centered grid. In fact, this modification is not required by the finite difference method, but it is needed by the computer program that will be used in this study.

With slight change that take the block-centered grid into account, equation (5.5) can be used to evaluate the first term in equation (4.20) :

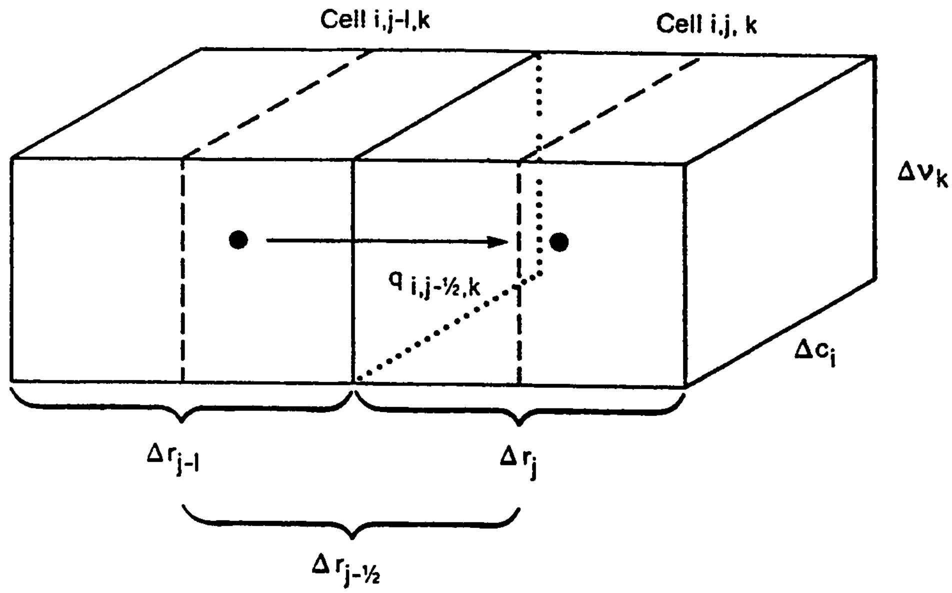
$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) = \frac{1}{\Delta x_i}\quad T\frac{\partial h}{\partial x}\bigg|_{i+½,j} - \frac{1}{\Delta x_i}\quad T\frac{\partial h}{\partial x}\bigg|_{i-½,j} \tag{5.17}$$

The first derivatives on the right side of equation (5.17) can be evaluated using equation (5.5). Therefore:

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right) = \frac{1}{\Delta x_i}\left\{T_{i+½,j}\frac{(h_{i+1,j} - h_{i,j})}{\Delta x_{i+½}} - T_{i-½,j}\frac{(h_{i,j} - h_{i-1,j})}{\Delta x_{i-½}}\right\} \tag{5.18}$$

In the same fasion, the y-derivative is derived :

$$\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right) = \frac{1}{\Delta y_j}\left\{T_{i,j+½}\frac{(h_{i,j+1} - h_{i,j})}{\Delta y_{j+½}} - T_{i,j-½}\frac{(h_{i,j} - h_{i,j-1})}{\Delta y_{i-½}}\right\} \tag{5.19}$$



Δr_J Dimension of Cell Along the Row Direction Subscript (J) Indicates the Number of the Column

Δc_I Dimension of Cell Along the Column Direction. Subscript (I) Indicates the Number of the Row

Δv_K Dimension of the Cell Along the Vertical Direction. Subscript (K) Indicates the Number of the Layer

Figure 5-3 Flow into cell i,j,k from cell i,j-l,k.

In evaluating the time derivative, a backward difference will be utilized :

$$\frac{\partial h}{\partial t} = \frac{h^{n}_{i,j} - h^{n-1}_{i,j}}{\Delta t} \tag{5.20}$$

Where:

$n =$ Time level $[\,T\,]$

Combining equation 5.20 with equations 5.18 and 5.19 gives :

$$\frac{1}{\Delta x_i}\left\{T_{i+\frac{1}{2},j}\frac{(h^{n}_{i+1,j} - h^{n}_{i,j})}{\Delta x_{i+\frac{1}{2}}} - T_{i-\frac{1}{2},j}\frac{(h^{n}_{i,j} - h^{n}_{i-1,j})}{\Delta x_{i-\frac{1}{2}}}\right\}$$

$$+ \frac{1}{\Delta y_j}\left\{T_{i,j+\frac{1}{2}}\frac{(h^{n}_{i,j+1} - h^{n}_{i,j})}{\Delta y_{j+\frac{1}{2}}} - T_{i,j-\frac{1}{2}},\frac{(h^{n}_{i,j} - h^{n}_{i,j-1})}{\Delta y_{j-\frac{1}{2}}}\right\}$$

$$+ W^{n} \approx S_{i,j}\frac{h^{n}_{i,j} - h^{n-1}_{i,j}}{\Delta t} \tag{5.21}$$

Equation (5.21) represents an algebraic equation which can be evaluated at each node. Taking care of the boundary and initial conditions relevant to the problem, and solving the resulting algebraic equations simultaneously via any numerical technique yields values of head at the predetermined nodes.

5. 3 Brief Description of Some of the Available Models

In 1975, Prickett made a literature review describing usage of groundwater models. He described, briefly, certain viscous fluid and electrical analog models, as well as some mathematical ones. In another research, Prickett (1979) addressed some pros and cons of groundwater modeling. He mentioned three reasons that put groundwater models into the class of intellectual toys, and another three reasons that made groundwater models very practical tools.

A general overview of groundwater modeling is, also, given by Mercer and Faust (1980a). They summarized modeling approaches, types of models, model use and misuse, limitations and sources of errors in modeling. In the second part of the series, Mercer and Faust (1980b) briefed basic processes of interest in groundwater application. They, also, showed how mathematical models are developed and gave some of the commonly used governing equations. Faust and Mercer (1980c) continued the series by presenting numerical models: finite difference models (FDM) and finite element models (FEM). They described the general initial and boundary conditions, the direct and iterative matrix solution methods as well as some special techniques. In the fourth episode of the series, Mercer and Faust (1980d) considered three examples (applications) in detail. In the last part of the series, Faust and Mercer (1980e) summarized some of the important research areas and significant modeling trends.

Another compact overview of groundwater modeling is given by Pinder (1988). In his article, Pinder documented, briefly, one perspective on the progress that had been made in groundwater modeling in the past two decades and of the advances that might be anticipated in years after 1988. He ended his article with a broad list of references related to groundwater modeling. Detailed information on groundwater models are available in Appel and Bredehoeft (1976), Bachmat et al. (1980), Mercer and Faust (1980a, 1980b). Comprehensive reviews of available models are presented by Prickett (1979), and Khondaker et al. (1990). Brief description of several available packages are given in the following paragraphs.

A Finite Element Aquifer Flow Model (AQUIFEM-1) is a two-dimensional finite element model for groundwater flow (Townley and Wilson, 1979). It employs the Galerkin finite element technique, with linear interpolation function and triangular element. Leakage from adjacent aquifers, pumping and recharge wells, lateral inflows, induced infiltration, rising water conditions, evapotranspiration, other boundary conditions, and source/sinks are accounted for. Both steady state and transient solutions for confined, phreatic, or mixed conditions can be computed.

AQUIFEM-1 is based on consistent set of units. It utilizes dynamic storage allocation. All input data are automatically checked for completeness and consistency.

USGS Two-Dimensional Groundwater Flow Model is a finite difference model for aquifer simulation in two dimensions. This model simulates groundwater flow in an artesian aquifer, a water table aquifer, or a combined artesian and water table aquifer. The aquifer may be heterogeneous and isotropic and may have irregular boundaries. The source term in the flow equation may include well discharge, constant recharge, leakage from the confining bed, and evapotranspiration as a linear function of depth to water.

The numerical techniques used in this model are an iterative alternate direction implicit procedure, a strongly implicit procedure, and a line successive over-relaxation scheme.

Illinois Water Survey Finite Difference Model. This model is a numerical solution of the two-dimensional, transient partial differential equation of groundwater flow. Its developed by Prickett and Lonnquist (Prickett and Lonnquist, 1971). One version of the model is able to simulate heterogeneous, confined aquifer with induced infiltration from the streams and variable pumping rates from wells. A second version of the program has identical capabilities but is able to solve a 50 by 50 finite difference grids by strong intermediate computations on a floppy disk during the simulation. A third version of the program is able to simulate heterogeneous aquifer under both confined and unconfined conditions with variable pumping rates from wells. A 24 by 24 finite difference grids may be simulated.

DREAM - Analytical Groundwater Flow Programs. This is a series of integrated computer programs which compute drawdowns, water level elevations, steady flow velocities, and steady-state streamlines based on the Theis equation and a uniform, regional flow gradient. A well-documented user's manual provides complete information on the IBM-based computer programs, directions for installation of the computer programs, and a description of the theory, execution and I.O format. It also includes a summary of the program features, and several well-documented examples written in a step-by-step tutorial format. It has the provisions of tabulated as well as graphical outputs as contours. Output format is compatible with a variety of commercially available contouring programs.

DREAM has great reliability in preliminary groundwater investigations because first-estimate interpretations can be made in a very short time. It also can be a very powerful tool in evaluating relatively simple groundwater flow systems, because the impact of changes in pumping rates, well locations, and parameter values can be visualized quickly in graphical forms.

5. 4 Selection of the Numerical Model

The above mentioned review of the available groundwater flow models is by no mean comprehensive. Furthermore, some of the packages have been recieving modifications and successive additions in order to enhance their capabilities. Such enhancements are giving the latest version of any model more power in solving a diversified groundwater flow problems. It is almost becoming bewildering to keep up with the research literature and the new softwares dealing with groundwater modeling.

Among the world-wide most famous packages, the *Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW)* appears to be on the top of the list. This model simulates flow in three dimensions using a block centered finite difference approach. Layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds can also be simulated. The modular structure of the program consists of a main program and a series of highly independent subroutines called modules. The modules are grouped into packages. Each package deals with specific features of the hydrologic system which is to be simulated. MODFLOW contains the strongly implicit procedure (SIP) or the slice-successive over-relaxation (SSOR) technique for solving linear equations which describe the flow system.

This package was developed by McDonald and Harbaugh (McDonald and Harbaugh, 1984) for the United States Geological Survey (USGS), and has gained world-wide recognition due to its capability to handle multi-layer aquifers and flexibility in its use under specific conditions. The USGS MODFLOW has successfully replaced its widely used predecessors USGS2D (Trescott, Pinder and Larson, 1976) and USGS3D (Trescott, 1975). The new code may be used for either two or quasi three-dimensional applications. The new model is simple to use and maintain and can be executed on a variety of computers with minimal changes. The program was originally written in Fortran 66 , but has been upgraded to be run on any Fortran 77 compilers.

The program is efficient with respect to computer memory and execution time because it utilizes modular structure wherein similar programming functions are grouped together. Specific comp- utational and hydrological options are constructed in such a way that each option is independent of the others (McDonald and Harbough, 1984).

The main program controls the execution order of the modules without interference in the finite difference equation, and regulates the work of other packages which add specified terms to the finite difference equation. Furthermore, the main program serves as a switching system for information. Packages which are completely independent of each other can be added or removed without affecting other packages (McDonald and Harbough, 1984).

The model contains the following packages (Al-Assar, 1992) :

1. The BASIC package discritizes space and time into cells and time steps. It specifies the initial and boundary conditions and heads at the beginning and end of time steps. The package specifies the program options to be used and controls the output results. It also gives a summary of the volumetric budget.

2. The WELL package simulates recharging and discharging wells.

3. The DRAIN package simulates leakage of an aquifer through a barred drain.

4. The RIVER package simulates infiltration of water through river beds.

5. The GENERAL HEAD BOUNDARY (GHB) package simulates special types of boundaries other than those simulated by the BASIC package.

6. The RECHARGE package simulates areal recharge from either surface waters or rainfall.

7. The EVAPOTRANSPIRATION (ET) package simulates evaporation and transpiration of both surface and subsurface waters.

8. The BLOCK CENTERED FLOW (BCF) package computes the conductance components of the finite difference equation which determines flow between adjacent cells. It also computes the terms that represent the rate of movement of water to and from storage.

9. The STRONGLY IMPLICIT PROCEDURE (SIP) package solves the set of equations to a predetermined accuracy.

10. The SUCCESSIVE OVER RELAXATION (SOR) package is an alternative package to solve the set of equations.

The model output usually consists of heads at various cells, and a volumetric budget. A more detailed output can be obtained by using the output control option. The model is capable to simulate groundwater flow in at both steady and at unsteady (transient) states. McDonald and Harbaugh (1984) made use of physical concepts regarding the flow system rather than sophisticated calculus techniques.

5. 5 Input Data Requirement for the Model

5. 5. 1 Study Area Discritization and Boundary Conditions

The spacing of the grid system was chosen carefully after some trials to check the hydraulic budget. The model is known to be sensitive to the grid size. The first trial assumed a cell width of 10 kilometers. It was noticed that a cluster of wells were to be closely located in a single cell. This produced problems in the water budget. A final grid size of 2 kilometers was accepted. The fine mesh was composed of 28 cells in the column direction (north-south) and 20 cells in the row direction (east-west) as in Figures 5.4 and 5.5. The total number of cells is 560.

The boundary conditions of the study area were determined after a thorough study of the prevailing conditions in 1983. Figures 5.4 and 5.5 show the discretized study area with the boundary conditions. The northen part of the Neogene aquifer was modeled as a *no-flow boundary (impermeable boundary)* (a special Neumann type condition) since the peizometric head lines were prpendicular to that boundary. Similarly, the south-eastern part was modeled as a no-flow boundary due to the same reason. The other boundaries were treated as *general head boundaries (head-dependent boundary)* because there exists no specific trend in the peizometric head map accross these boundaries. General head boundary means that flow into or out of a cell from an external source is provided in proportion to the difference between the head in the cell and the head assigned to the external source (McDonald and Harbaugh, 1984). Therefore, a linear relationship between flow into the cell and head in the cell is established:

$$Q_b = C_b (h_b - h) \tag{5.22}$$

where:

Q_b = the flow into the cell from the source

C_b = the conductance between the external source and the cell

h_b = the head assigned to the external source

h = the head in the cell.

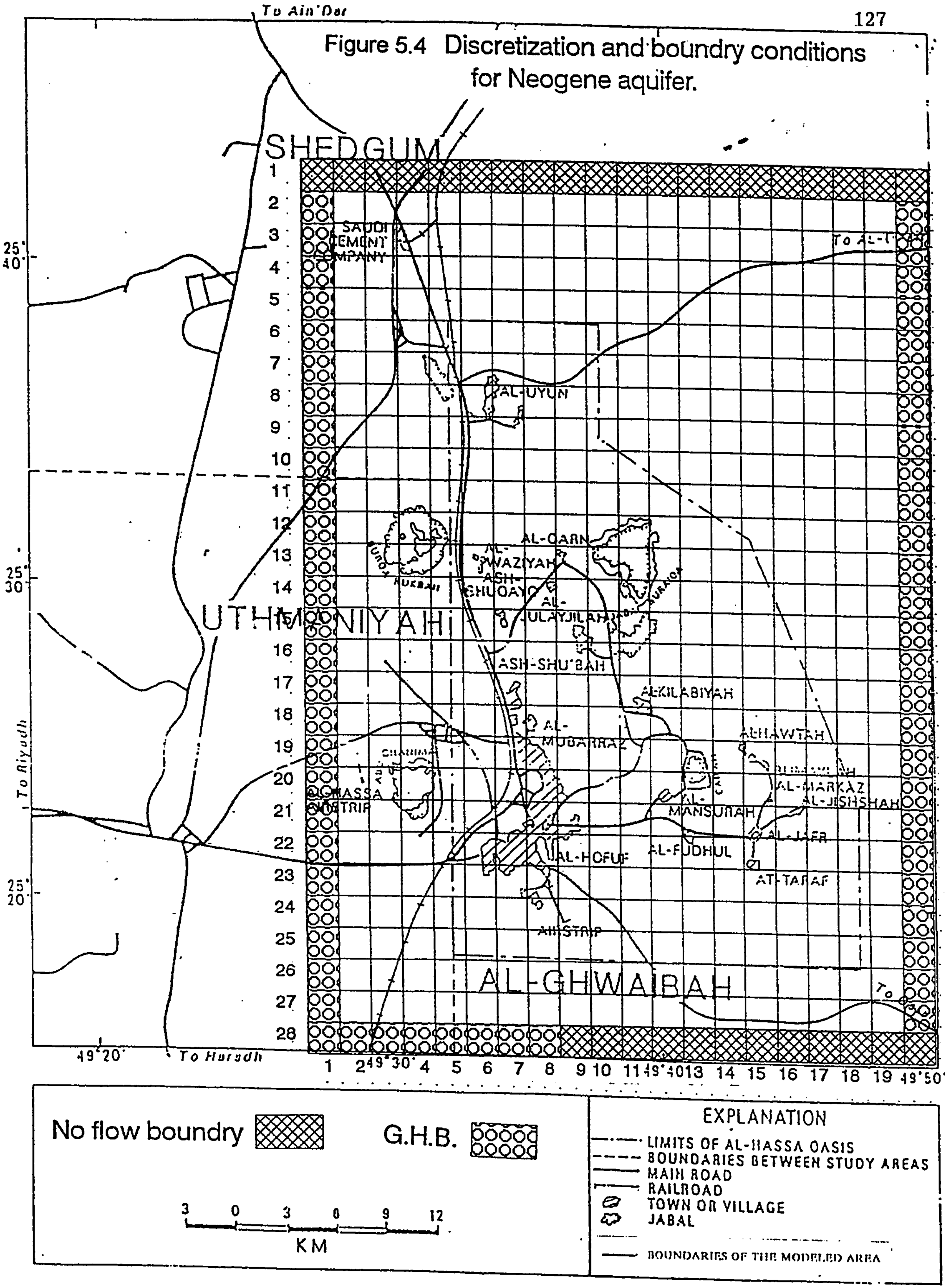


Figure 5.4 Discretization and boundry conditions for Neogene aquifer.

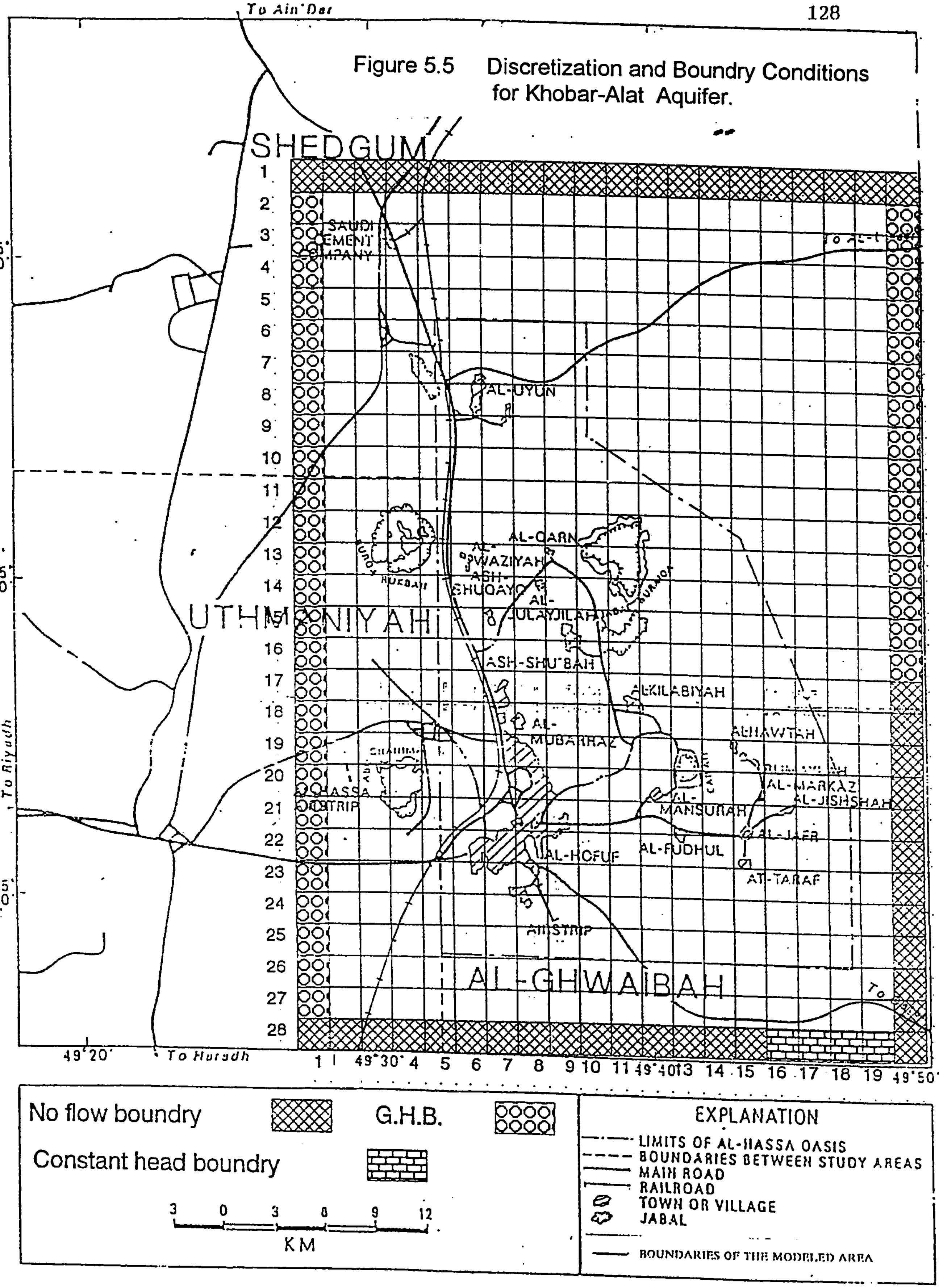


Figure 5.5 Discretization and Boundry Conditions for Khobar-Alat Aquifer.

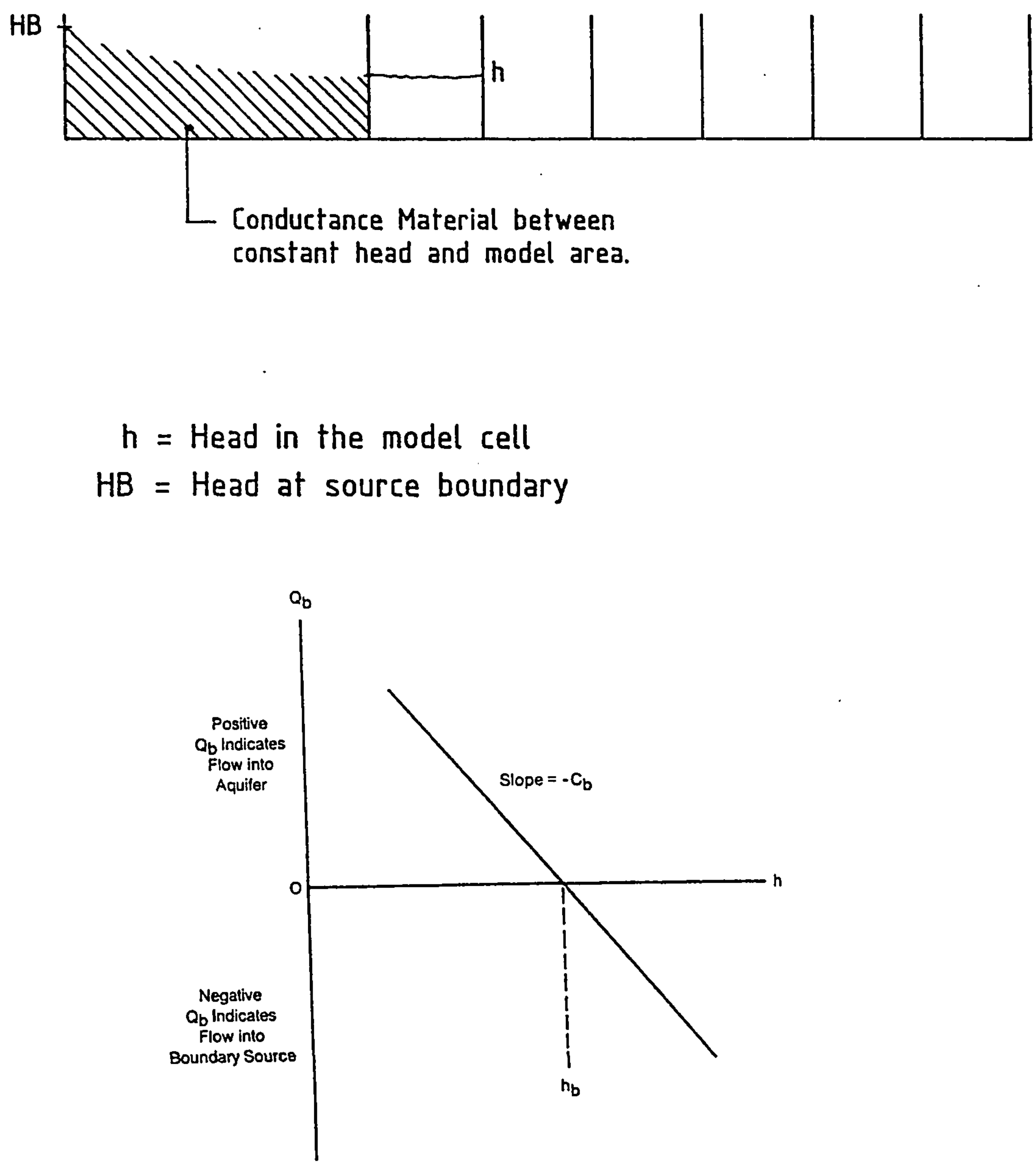


Figure 5.6 Constant Head Boundary Outside the Model Area (after McDonald and Harbough, 1984).

The relationship between the cell and the external source is shown schematically in Figure 5.6. In this study, the external source is considered to be the head in the aquifers outside the modelled area. It is determined 20 kilometers away from both sides by the knowledge of the hydraulic gradient in the area to insure that the source cells do not affect the modeled area. The conductance which is the proportionality constant in equation (5.22) is computed by:

$$C_b = \frac{TW}{L} \tag{5.23}$$

where:

T = transmissivity of the aquifer between the external source and the model boundary

W = width of the cell

L = the distance between the external source and the model boundary

The heads at the source boundaries were calculated based on the hydraulic gradient in the area. The conductance terms were calculated based on the average transmissivity values and the distance to the source boundaries. The head dependent boundaries are handled by the General Head Boundary package of the model.

On the other hand, the Khobar-Alat aquifer exhibited different peizometric heads at the southern part. Hence, most of the southern boundary was modeled as *no-flow*. The peizometric heads can be clearly noticed to be perpendicular on that particular boundary. The eastern part of the southern boundary was modeled as a *constant head boundary* (Dirichlet condition). The peizometric surface lines were parallel to that part of the boundary up to the extent of 10 kilometers outside the modeled area. The remaining boundaries were modeled as general head boundaries. To jutify the choice for these boundaries, heads were studied outside the simulated region to make sure that these are not local variations in the peizometric heads.

Very few wells penetrate Umm er Radhuma aquifer. The flow from Umm er Radhuma aquifer to Khobar-Alat - and eventually to the Neogene- aquifer was observed to be influenced only by the pumping from the Neogene aquifer. Therefore, the resulting heads in the Umm er Radhuma aquifer are similar to these in the Khobar-Alat aquifer. It was, then, decided to eliminate simulation of the Umm er Radhuma aquifer and replace the flow to Khobar-Alat by a vertically upward leakage.

5. 5. 2 Initial Piezometric Surface

Initial piezometric surfaces of the aquifers in the study area are presented in Figures 5.7 and 5.8. These maps were constructed on the basis of data released by Al-Hasa Irrigation and Drainage Authority (HIDA). These heads represent those observed in 1983. Since the study area was in dynamic mode, ther was no sense in developing steady state heads. However, the heads recorded in 1983 were taken to be the initial heads for the unsteady simulation. It is obvious from Figure 5.7 that the Neogene aquifer was being stressed

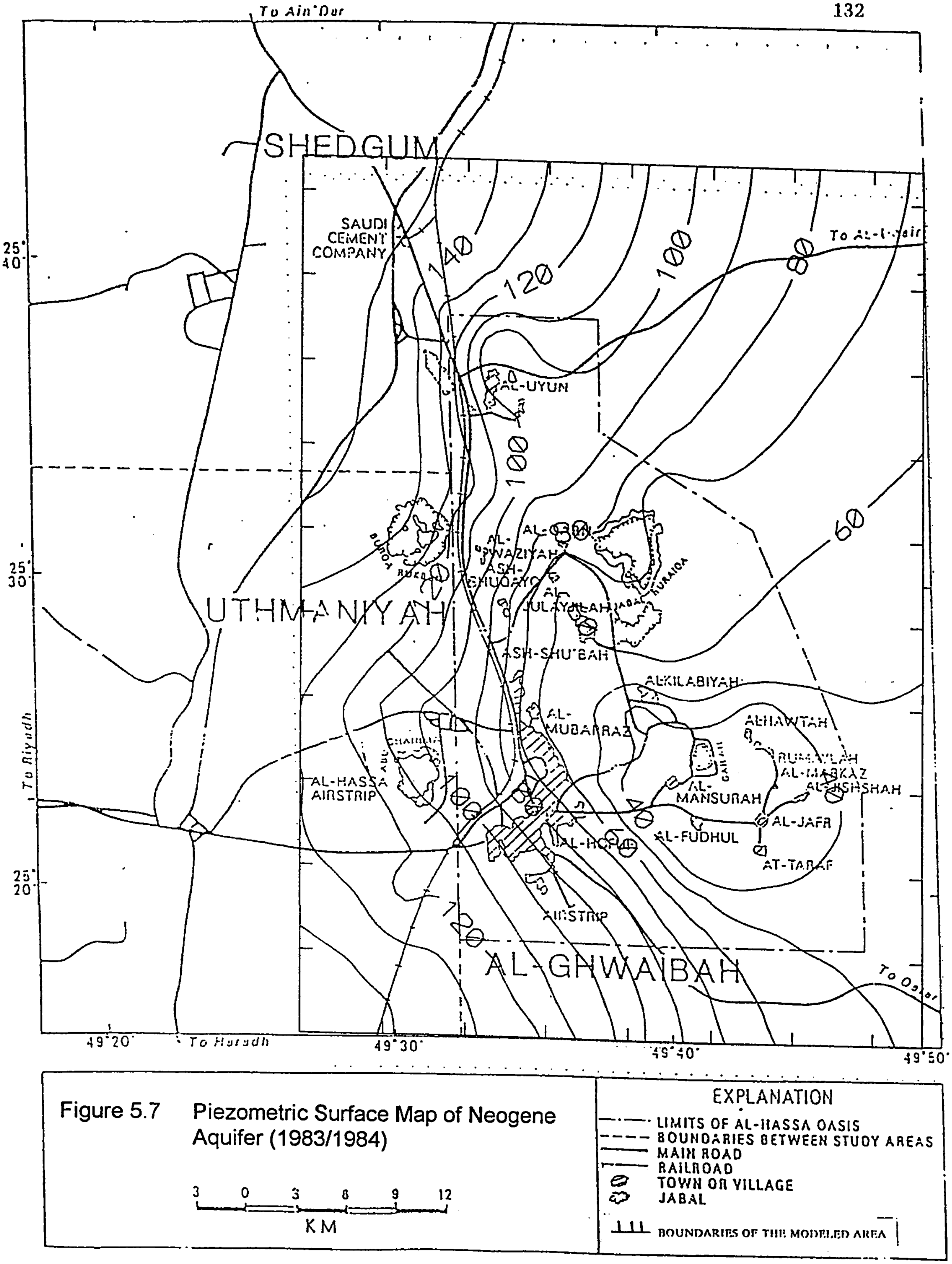


Figure 5.7 Piezometric Surface Map of Neogene Aquifer (1983/1984)

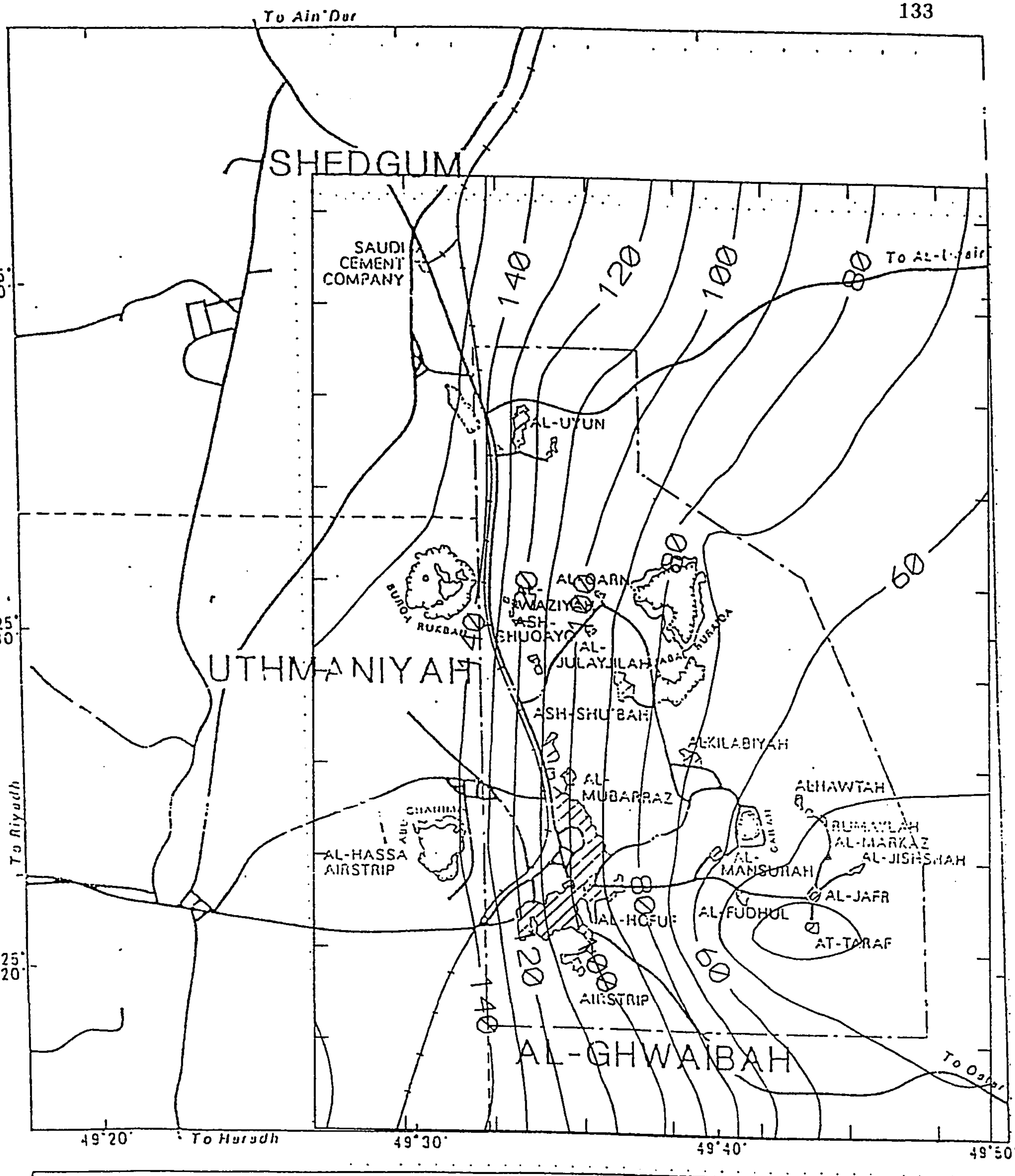


Figure 5.8 Piezometric Surface Map of Khobar-Alat Aquifer (1983/1984)

heavily in the southeastern part. The cone of depression can be noticed clearly.

The observed heads of layer 2 (Khobar-Alat aquifer) supports that there is a strong interaction between it and the Neogene aquifer in the area. Although there are few wells drilled in this aquifer, there exists a cone of depression almost below the cone of depression in the upper Neogene aquifer.

The two aquifers (the Neogene and Khobar-Alat) exhibit the same hydraulic gradient. The hydraulic gradient is about 5 to 10 meters per kilometer. The high hydraulic gradient is due to the high pumping rates and the huge quantities of water extracted.

5. 5. 3 Extraction Rates

Al-Hasa Irrigation and Drainage Authority (HIDA) consumes the major part of Al-Hasa groundwater. The the total extracetd rate by HIDA and other consumers in 1980 was about 9.6 m^3/s . This is totally used for irrigation. The domestic water consumption in the Oasis in 1982 was 1.408 m^3/s. In 1982-1983 the Al-Hasa industrial sector used around 0.3 m^3/s. This quantity was used by small food and dairy factories (Abderrahman and Ukayli, 1984).

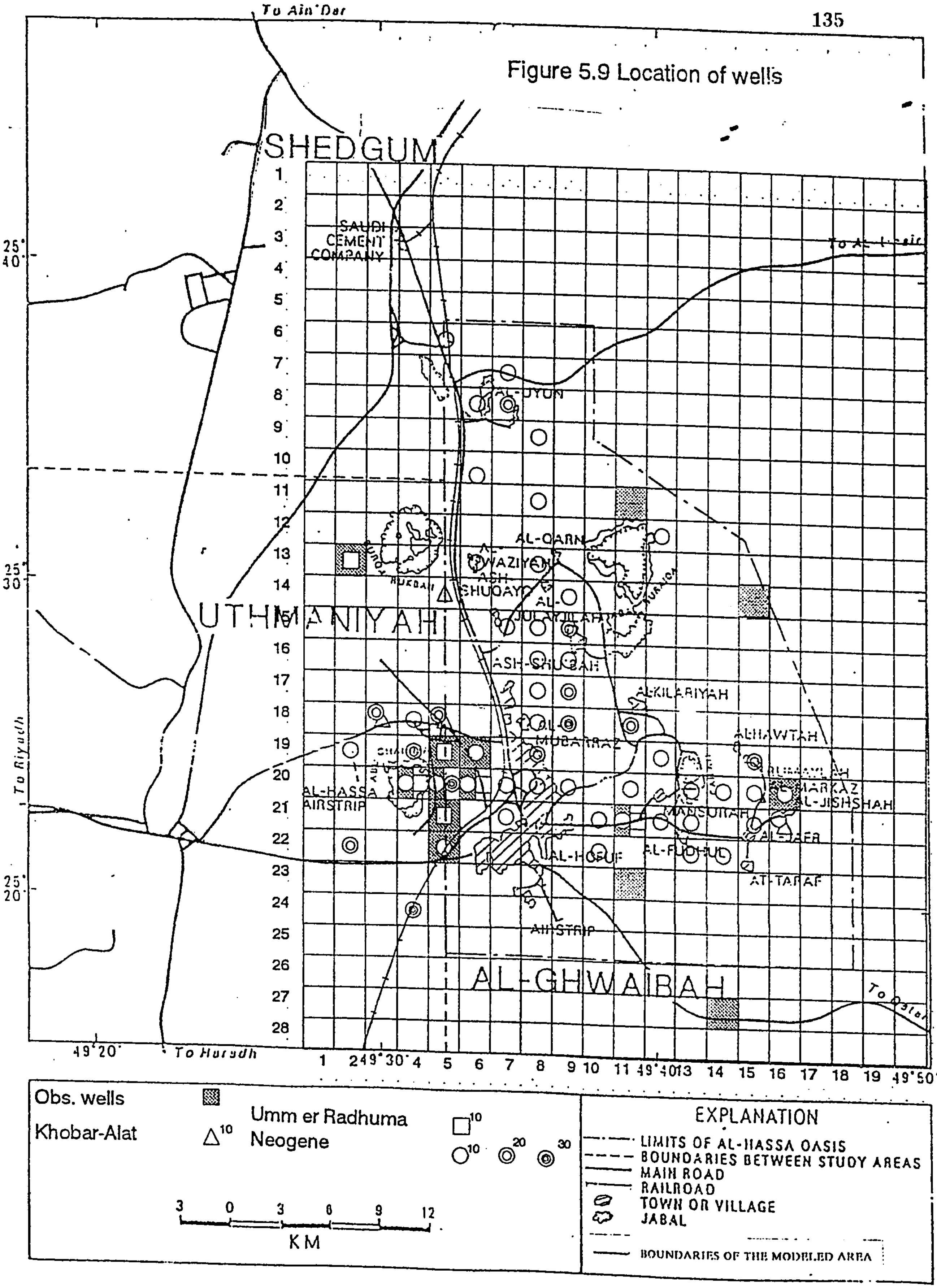


Figure 5.9 Location of wells

The wells presented in Table 3.3 (chapter 3) were located accurately in the study area. Figure 5.9 shows the cells that contain these wells. The discharge rates were summed up for the wells that are located in the same cell. One would notice that these wells are concentrated in between rows 14 and 22 and columns 3 and 16. This explains the location of the cone of depression previously seen in Figures 5.7 and 5.8. The pumping rates from these wells ranged from 0.02 to 0.05 m^3/s. .

There are very few wells penetrating the Khobar-Alat and Umm er Radhuma aquifers in the study area. Most of these were shut down in the 1980's. One can conclude that the major, if not the sole, water extracted is from the Neogene aquifer. Indeed, this has been conformed by Abderrahman and Ukayli (1984).

5. 5. 4 Initial Assessment of Input Parameters

Transmissivity (T) and Storativity (S)

Transmissivity and storativity of the aquifers have been determined by Italconsult (1969) and GDC (1980). Also, they were included in a thesis by Al-Mahmoud (1987) who analyzed the pumping test data of both the Arabian-American Oil Company (ARAMCO) and BRGM. The results were presented in Tables 3.4 and 3.5. The drawdown curves analyzed by Al-Mahmoud suggested that the main water-producing zone of the Umm er Radhuma Formation in the test locations is the upper one third of the aquifer. It was, also, found that the transmissivity values of all aquifers decrease as the distance from the Ghawar anticline increases. This might be attributed to the decrease of fracturing in the aquifers rocks away from the anticline crest.

The analysis of the pumping tests suggests a low transmissivity of Umm er Radhuma in the area south of Hofuf. The sudden change in the Umm er Radhuma transmissivity in the Al-Hofuf area is most likely due to variations in the lithology and textural properties of the formation in that area (Al-Mahmoud, 1987). On the other hand, the pumping test conducted at Al-Mubarraz by ARAMCO in 1985 indicated that the Neogene Group is highly transmissive. However, this is not true for the whole area due to the great facies variations in the Neogene Group.

Due to the above mentioned factors, the transmissivity and storativity spatial variations were determined and presented in Tables 5.1, 5.2 and 5.3. The values are given for the complete set of rows and columns that covers the whole study area. These values were used in the simulation and later calibrated to arrive at a suitable match between observed and simulated heads. The values given in the work of Al-Mahmoud (1987) outside the study area were used to find the conductance relevant to the general head boundaries.

Table 5.1 Transmissivity and Storitivity values of Umm Er Radhuma Aquifer

i	j	T	S
		[m^2/day]	
1 → 28	1 → 5	52704	1.21E-04
1 → 28	6 → 10	475.2	1.10E-05
1 → 28	11 → 20	59	6.50E-05

(After Al-Mahmoud, 1987)

Table 5.2 Transmissivity and Storitivity values of Khobar-Alat Aquifer

i	j	T	S
.		[m^2/day]	
1 → 7	1 → 20	15	2.00E-04
8 → 14	1 → 20	441	
15 → 21	1 → 20	3024	
22 → 28	1 → 20	39	

(After Al-Mahmoud, 1987)

Table 5.3 Transmissivity and Storitivity values of Neogene Aquifer

i	j	T	S
		[m^2/day]	
1 ↓ 14	1 ↓ 20	225	2.00E-04
15 ↓ 25	1 ↓ 10	1123	
	11 ↓ 20	225	
26 ↓ 28	1 ↓ 10	562	
	11 ↓ 20	225	

(After Al-Mahmoud, 1987)

Leakage Coefficient (Vertical Leakance, $\underline{VLeak}$)

Vertical flow through a confining layer is a function of the vertical hydraulic conductivity, the thickness of the the confining unit, and the head difference accross the bed. The three aquifers in this study are known to be hydraulically connected through leaky aquitards. The amount of leakage depends on the parameters of these aquitards, as mentioned above. Actual measured values of the vertical leakances are scarce. Some values are given by BRGM (1977) and GDC (1980). Those values are reported by Rasheeduddin (1988).

The Rus aquitard, between Umm er Radhuma and Khobar-Alat aquifers, has vertical leakances that range from 0.9×10^{-5} to 0.9×10^{-2} per day. The minimum values are found in the northern part of the study area. These values were mainly derived from GDC (1980).

The Alat marl aquitard, between Khobar-Alat and Neogene aquifers, showed a range of vertical leakance between 1×10^{-5} to 8×10^{-3} per day. These are obtained from BRGM (1977) and GDC (1980) works. These values were used during the simulation process in all cells with known vertical leakance values. Other values were assumed for the cells with unknown vertical leakance values.

5. 6 Model Calibration

5. 6. 1 General

Model calibration - in groundwater modeling sense- is the identification of variations and adjustment of aquifer and aquitard parameters until the computed heads match the observed values within an acceptable range of accuracy. The goal of most computer simulations is to predict the effects of some proposed management schemes on a particular groundwater system. The final test of a numerical model is to determine whether it successfully simulates field observations. Such a model is said to be calibrated and verified. This is needed to overcome the uncertainities in the initially assesed aquifer and aquitard parameters.

In general, the first step in model calibration is to design a steady-state model to solve for the head distribution to be used as the initial conditions in a later transient simulation. Because the study area was never exposed to a steady states since 1983, only transient calibration was carried out. The trial and error procedure has been adopted in the present study to calibrate the model. The model parameters such as transmissivities and storativities have been adjusted to obtain a suitable match between observed and simulated heads.

5. 6. 2 Transient Calibration

The calibration process involves the adjustment of transmissivity and storativity values in the study area. Boundary conditions have not been altered at this stage. The aquifers were judged confined and modelled as a layer type 'O' (McDonald and Harbough 1984). The calibration process was terminated after a satisfactory match was reached at. At this stage the simulated heads were reasonably in accordance with the observed heads. This can be seen in Figures 5.10, 5.11 and 5.12 which show the hydrographs of observed simulated heads at cells (11,11), (23,11) and (14,15). It is noticed that the calbrated transmissivity values are not very different from those used initially.

Not only the spatial variations in piezometric heads are important, but also the temporal variations are of concern. Transient calibration is carried out to adequately describe the hydraulic changes in the aquifer with time. Transient calibration involves the change of aquifer parameters so that the historical records of heads match those obtained from the simulation. In this regard, the model has been calibrated from 1983 to 1992.

Figures 5.10 and 5.11 show that simulated heads are less than the observed ones in the period from 1986 to 1991. This is may be a result of heavy pumping and low recharge in those years. Unfortunately, nothing can be emphasized about recharge due to lack in available field data. However, it is known that pumpage increase is a

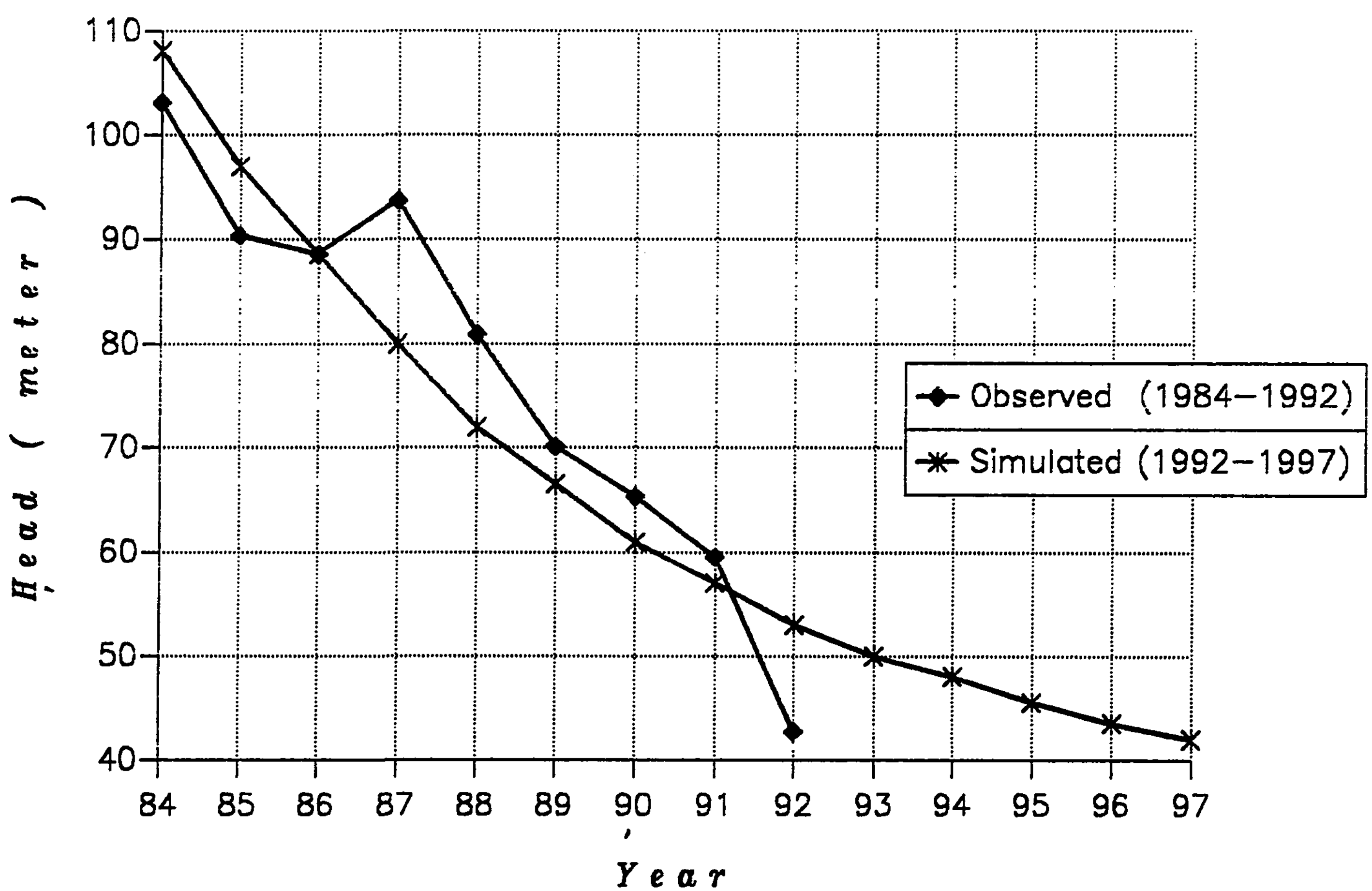


Figure 5.10 : Heads at Cell (11,11)
(Calibration Period 1984–1992)

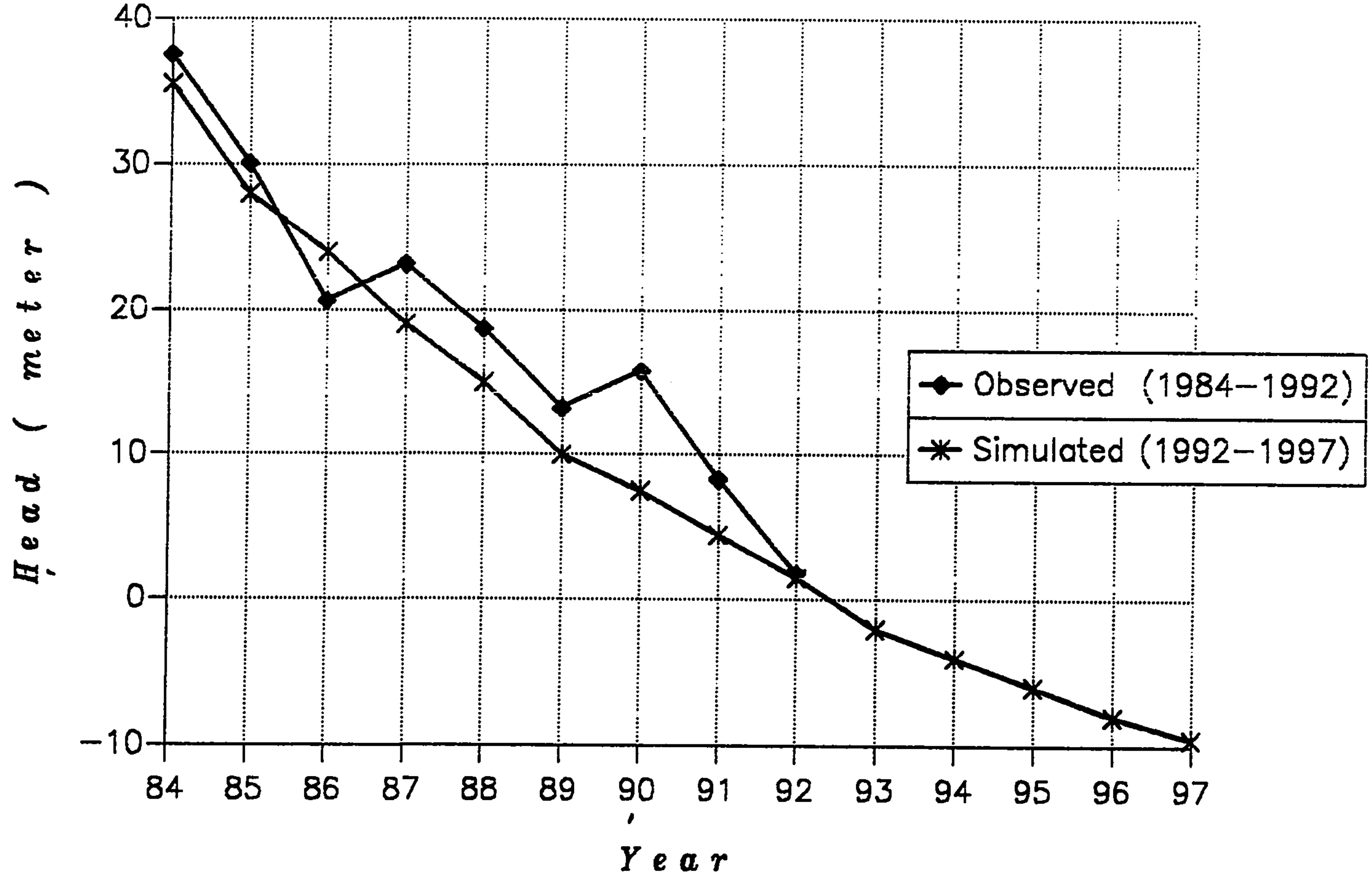


Figure 5.11 : Heads at Cell (23,11)
(Calibration Period 1984–1992)

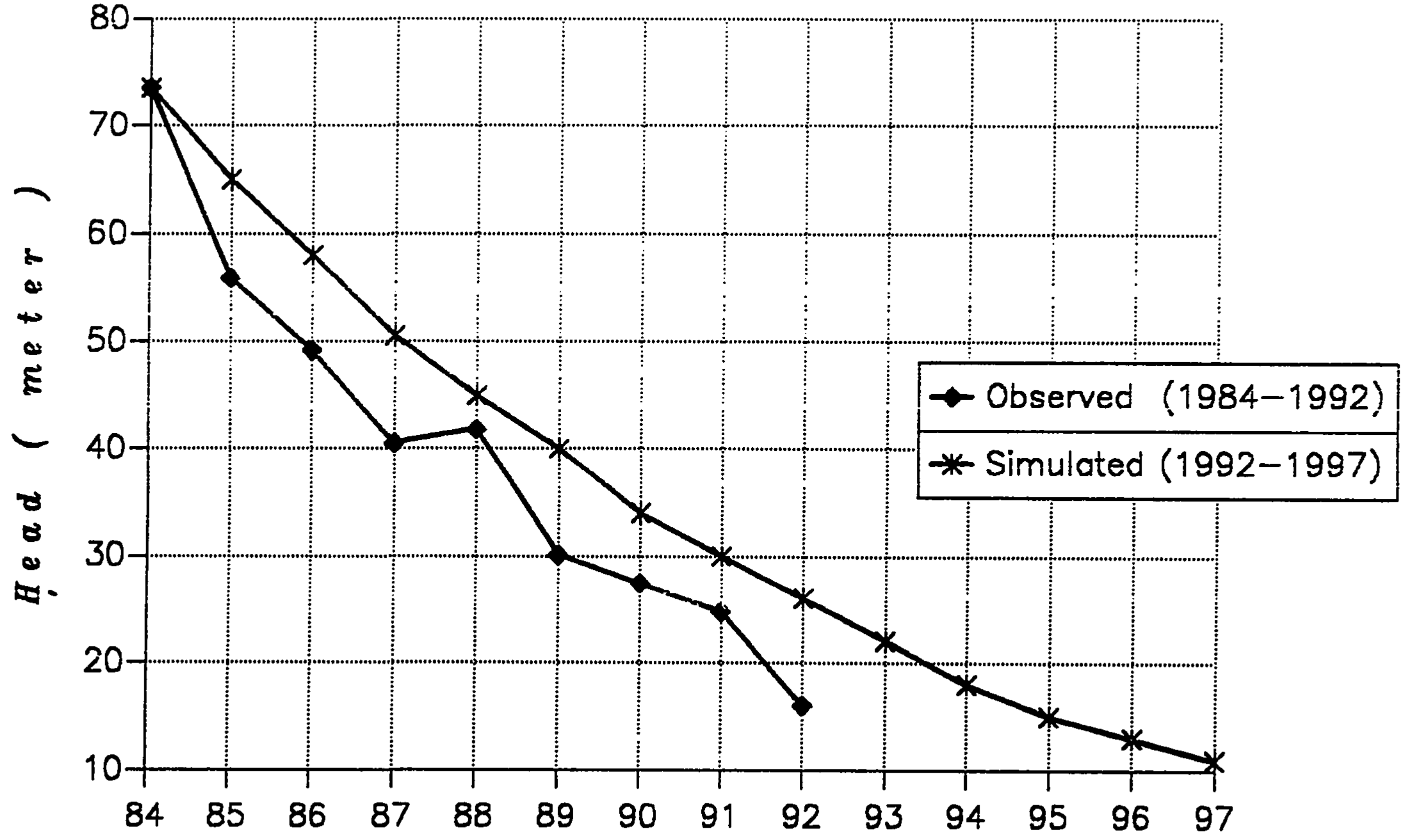


Figure 5.12 : Heads at Cell (14,15)
(Calibration Period 1984–1992)

real fact in Al-Hasa during the 1980s period.

The transient calibration of the storativity values was conducted. The storativity calibrated seems to be of little spatial variations. Rasheeduddin (1989) supports this fact by reaching to a constant storativity of 4×10^{-4} in an area of 9400 square kilometers. Appendix A contains the graphs of the piezometric heads at the end of each of the nine stress periods. It can be noticed that the model predicts increase in drawdowns.

Upon a close look at the simulated heads, it can be concluded that a cone of depression exists in the southern part of the study area. This is due to the concentration of discharging wells in that locality. There is an average drop of head equal to 5 meters per year. The total drop of head in the simulation period is about 50 meters. The spatial distribution drowdown are presented in the Appendix.

Chapter 6

MANAGEMENT ALTERNATIVES

6. 1 Introduction

Once a computer model is calibrated and verified, it becomes ready to be used for forecasting purposes. Prediction of changes in heads according to prescribed scenarios is the ultimate goal of the simulation process.

There are many alternatives that can be considered at any time. However, only those relevant from a cost and environmental point of view should be taken into account. Furthermore, an implemented alternative should fulfill the future water demand without contradicting legal or political aspects. In this regard, two alternatives have been considered. The heads and drawdowns associated with each scenario for the next five years have been generated. These alternatives are : *no growth,* and *reduction in consumed water.* These scenarios were selected based on various alternatives suggested by several researchers ((BRGM, 1977), (Abderrahman and Ukayli, 1984), and (Abderrahman, 1988)).

For each alternative, a planning interval of five years (1992-1997) was selected. The starting time for prediction was the end of 1992.

For every alternative, drawdown maps at the end of each stress period were constructed. This was made via subtraction of resulting simulated heads from those of the initial heads. Such maps are advantageous in clarifying both the location and the extent of any existing cone of depression.

6. 2 Alternative I : No Growth

The existing trend in the last simulation year of 1991/1992 are assumed to prevail for the next five years. Five extra stress periods were added to the modelled time to represent this. The extraction rates are kept at the same levels as those presented in the previous chapter (section 5.5.3). Figures 6.1, and 6.2 show the predicted heads by the year 1996/1997. It is noticed that the cone of depression remains to be in south middle part of the study area. The drop in head rate is almost the same as that for the simulation period (5 m/ year). The drawdowns are presented in Figures 6.3 and 6.4. Higher drawdowns are observed in the western part of the study area. The continuous drop of heads is due to continued discharge from wells. There is no recovery period except in very few places.

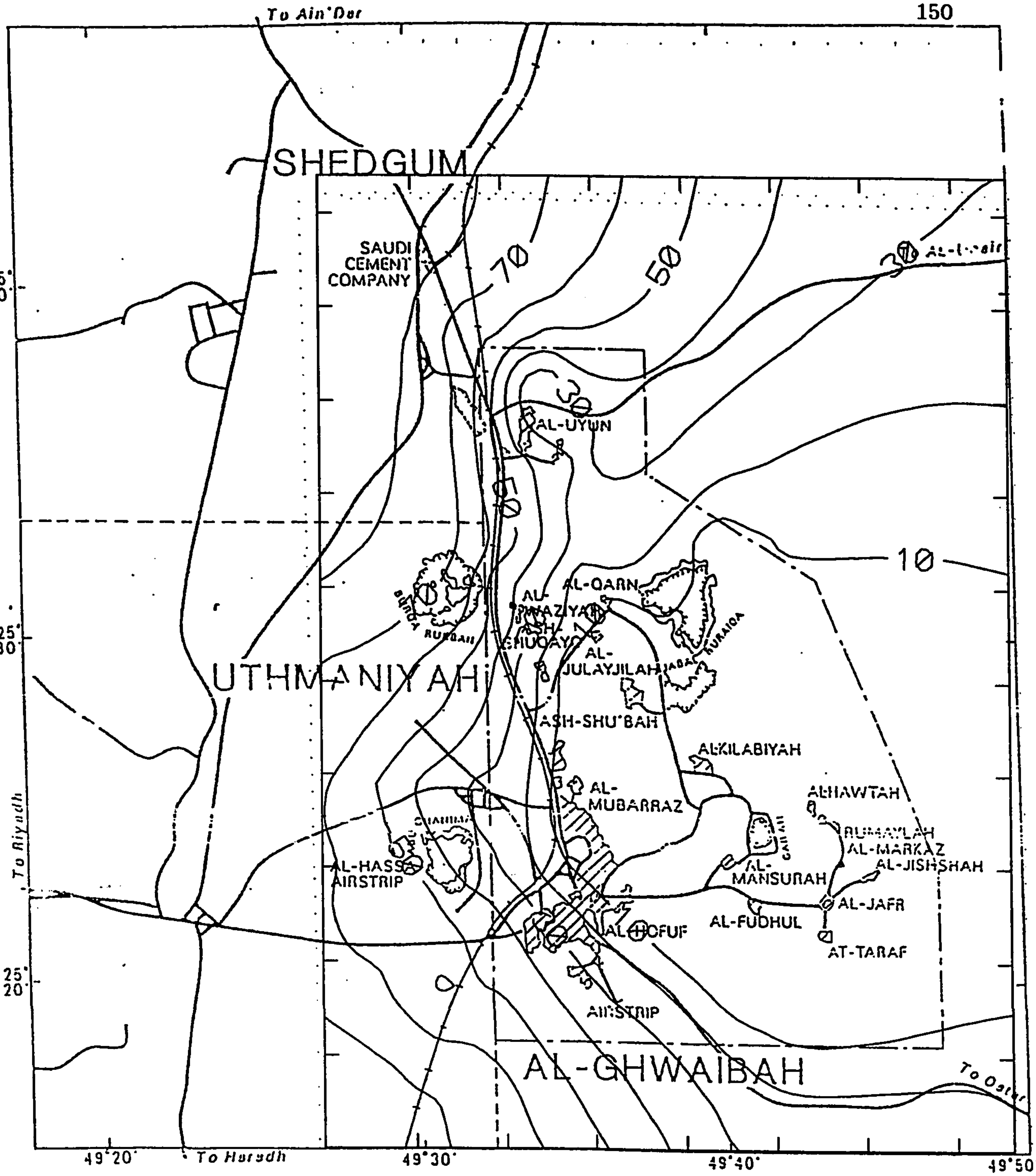


Figure 6.1 Predicted Heads in Neogene Aquifer/ Al-Hasa Oasis 1997

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

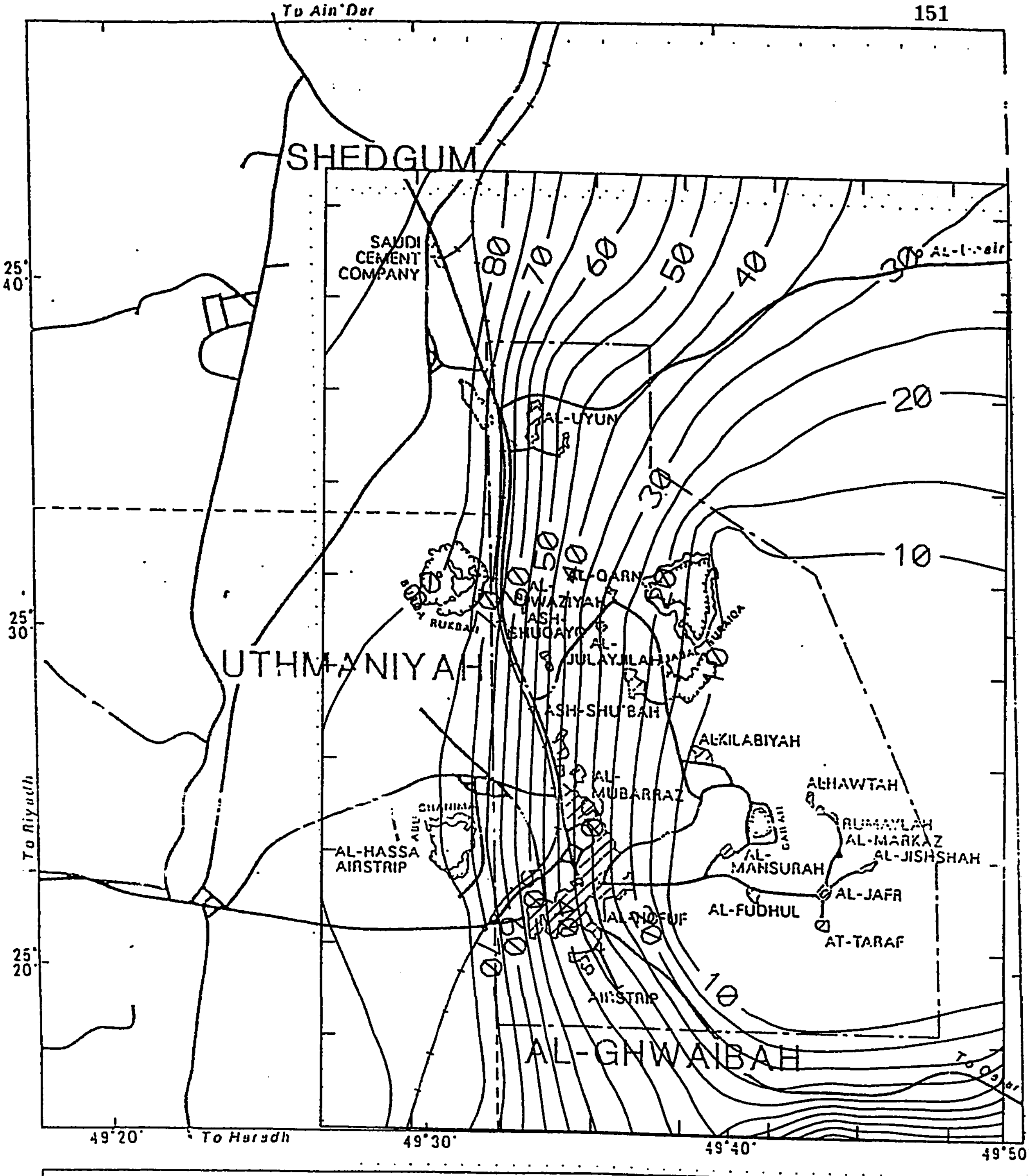


Figure 6.2 Predicted Heads in Khobar-Alat Aquifer/Al-Hasa Oasis 1997

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

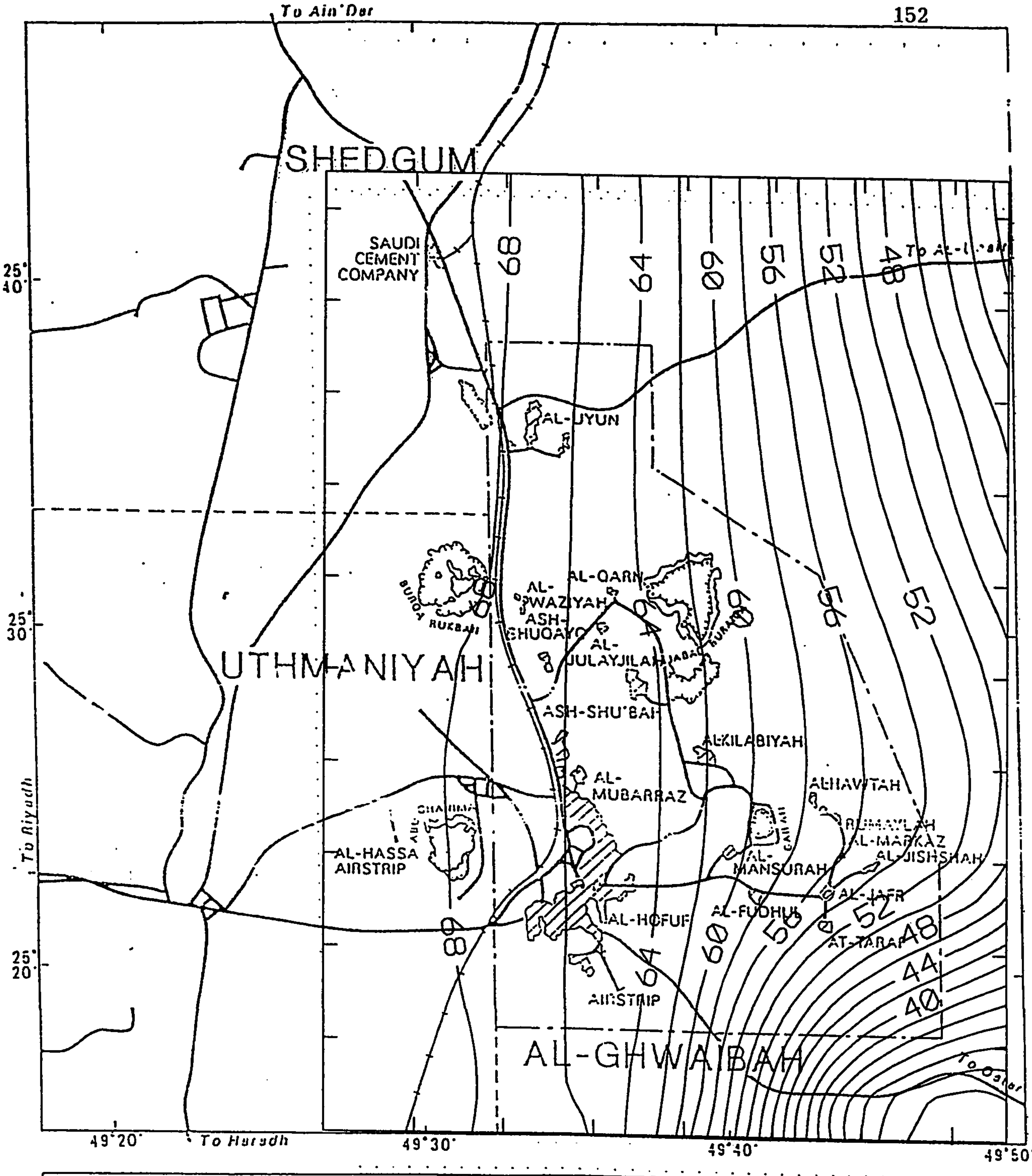


Figure 6.3 Predicted Drawdowns in Neogene Aquifer/Al-Hasa Oasis 1997

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

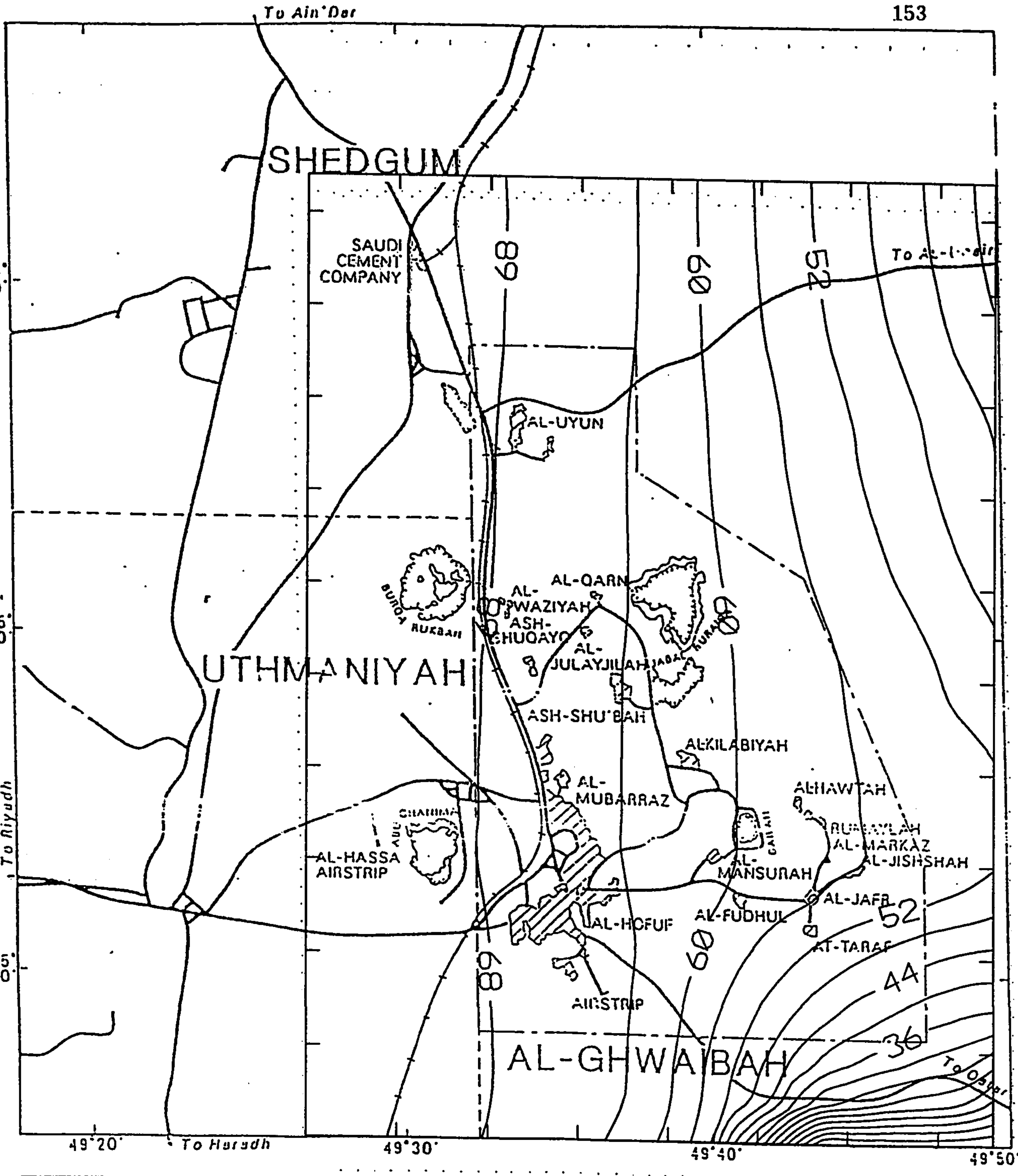


Figure 6.4 Predicted Drawdowns in Khobar-Alat Aquifer/Al-Hasa Oasis 1997

3 0 3 6 9 12

KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

6. 3 Alternative II : Conservation

Water conservation includes any feasible tools that minimize losses and improve water relevant managerial practices. Water conservation is becoming more and more needed in Saudi Arabia as water consumption is increasing while available water resources are limited. The rational utilization of the scarce water supplies has been of great concern in Saudi Forth and Fifth Development Plans.

In general, conservation efforts are made in domestic uses. These uses have low contribution to the total water consumed. But, on the other hand, their costs are higher than that of other uses ((Rasheeduddin, 1988), (Khan and Abdulrazzak, 1986)). In Al-Hasa, the domestic water consumption in 1982 mounted to 1.41 m^3/s and is expected to be around 2.5 m^3/s in 1993. The forecasted grand total water demand in 1993 is 19.6 m^3/s (Abderrahman and Ukayli, 1984). This means that the domestic uses compromises about 12.8 % of the total consumption.

A study by Khan and Abdulrazzak (1986) indicated that the saudi per capita consumption can be reduced by 30 - 50 % (which is equivalent to 3.83 - 6.38 % lowering in the total water used). The 30 % reduction can be achieved by using water saving devices, lowering the pressure in water mains, and developing public awareness. The 50 % reduction in domestic uses can be reached if all the previous tools are applied concurrently with imposing penalties on excess water use and reducing plumbing fixtures.

Besides conservation in domestic water uses, Al-Hasa Oasis needs water conservation in irrigation sector. Indeed, the bulk volume of the Oasis groundwater is utilized for irrigation purposes. Al-Hasa Irrigation and Drainage Authority (HIDA) records showed that the annual irrigation consumption was about 9.6 m^3/s between 1977 and 1983. This includes the 7.1 m^3/s used by HIDA itself in addition to 2.5 m^3/s discharged from private wells and springs. The total irrigation water demand forecasted by Abderrahman and Ukayli (1984) is about 15.85 m^3/s in 1990. No further increases in irrigation areas - and, hence, in irrigation water demand - are expected beyond 1990 (Abderrahman and Ukayli, 1984).

Studies have shown that a lot of water can be conserved by utilizing other sources, or by better management of extracted water. One alternative to using groundwater sololely is to irrigate with *non-conventional water sources.* These non-traditional sources include the reuse of *treated sewage effluent* and *agricultural drainage water.* Figure 3.24 shows the location of of the sewage treatment plants in Al-Hasa. All physical, chemical and biological properties of the treated effluent will meet the irrigation water standards of the Food and Agricultural Organization (FAO) of 1976. The range of expected quantities of

Table 6.1 Possible Means For The Reduction Of Al Hasa Groundwater Withdrawal: Upper Limit Reduction (Base Year 1993)

Expected Total Groundwater Demand (1993) =19.4 cubic m/sec.

Source	Reduction cubic m^3/sec	Reduction %
Treated Sewage	2.74	14.12
Agrcultural Drainage	3.44	17.73
Automation	1.42	7.32
Total Saving	7.60	39.17

(After Abderrahman and Ukayli, 1984)

treated effluent is 1.72 - 2.74 m^3/s in the period 1985-1993.

The other non-conventional source is the agricultural drainage water. There are two evaporation lakes in Al-Hasa (Figure 3.24) receiving about 2.693 m^3/s drainage water. Using the secondary treated sewage in irrigation, the drainage water will go up to nearly 3.44 m^3/s in 1993. Most cultivated crops in Al-Hasa can tolerate a salinity level of 2000 part per million (ppm). The salinity of agricultural drainage water can be always lowered to that level (i.e. 2000 ppm) by blending with fresh spring water and/ or mixing with the secondary treated sewage (Abderrahman, 1988).

Measures to reduce irrigation water demand include *Automation.* This implies a computerized control of all gates on irrigation canals. Gates and valves can be adjusted to release water according to irrigation requirements. Via Automation, only the needed water quantities will be discharged from springs and wells. Hence, most water losses from springs and canals will be saved. Automation of Al-Hasa irrigation system is expected to save 20 % of the presently used 7.1 m^3/s of irrigation water (Abderrahman, 1988).

The above conservation methods suggest that a considerable reduction in pumpage can be achieved. The lower bound of water saved is no less than 29 % and it can reach as high as 39 % without even taking into account the saves in domestic uses.

Table 6.2 Possible Means For The Reduction Of Al Hasa Groundwater Withdrawal: Lower LImit Reduction (Base Year 1993)

Expected Total Groundwater Demand (1993) = 19.4 cubic m/sec.

Source	Reduction cubic m^3/sec	Reduction %
Treated Sewage	1.72	8.87
Agrcultural Drainage	2.69	13.87
Automation	1.42	7.32
Total Saving	5.83	30.06

(After Abderrahman and Ukayli, 1984)

Table 6.2 reflects the contribution of the three techniques discussed in the previous paragraphs that can be used in pumpage reduction. The expected total water demand of 1993, that is 19.6 m^3/s, is used as a base for relevant calculations.

Two runs were executed representing the 29 % and 39 % reduction. The heads resulting from these reductions are presented in Figures 6.5, 6.6, 6.7, and 6.8 for both Neogene and Khobar-Alat aquifers. One can notice that the cone of depression is still located in the southern central part of the study area. However, the heads are lower than those expected if the usual practice was continued. The drawdowns are also plotted in Figures 6.9, 6.10, 6.11, and 6.12. To quantify the saved heads, the differences between the heads in this alternative and those obtained in alternative I are shown in Figures 6.13, 6.14, 6.15, and 6.16.

Figure 6.13 shows that the saving in heads corresponding to 29 % reduction is, almost, negligible in the western part of the study area. However, the saving in heads is considerable at the cone of depression area. This can, also, be noticed in Khobar-Alat aquifer (Figure 6.14). The 39 % reduction results in a more saved heads at the cone of depression (Figures 6.15 and 6.16). In general, it can be concluded that a remarkable save in heads is associated with 29 % and 39 % reductions in extracted water.

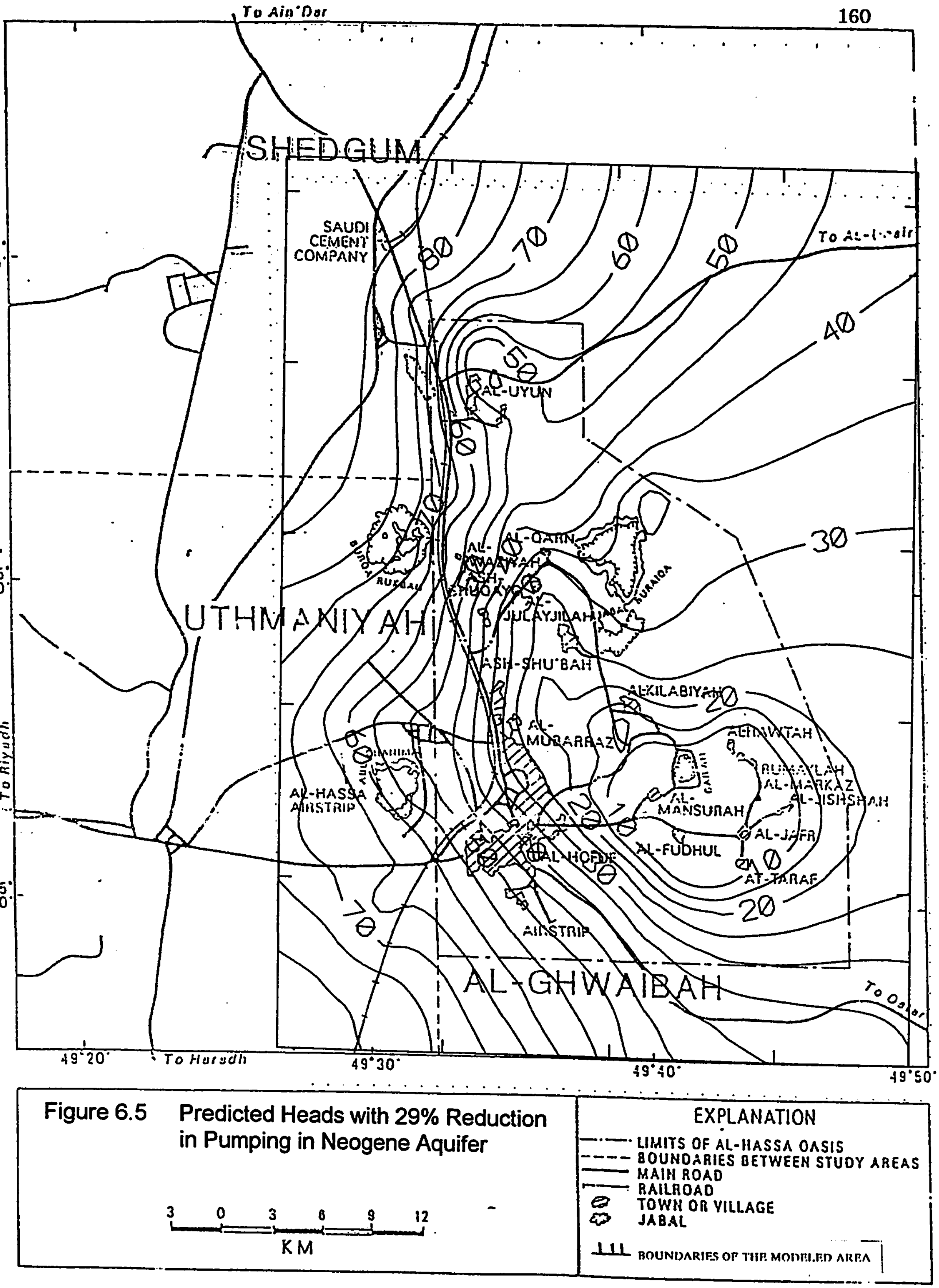


Figure 6.5 Predicted Heads with 29% Reduction in Pumping in Neogene Aquifer

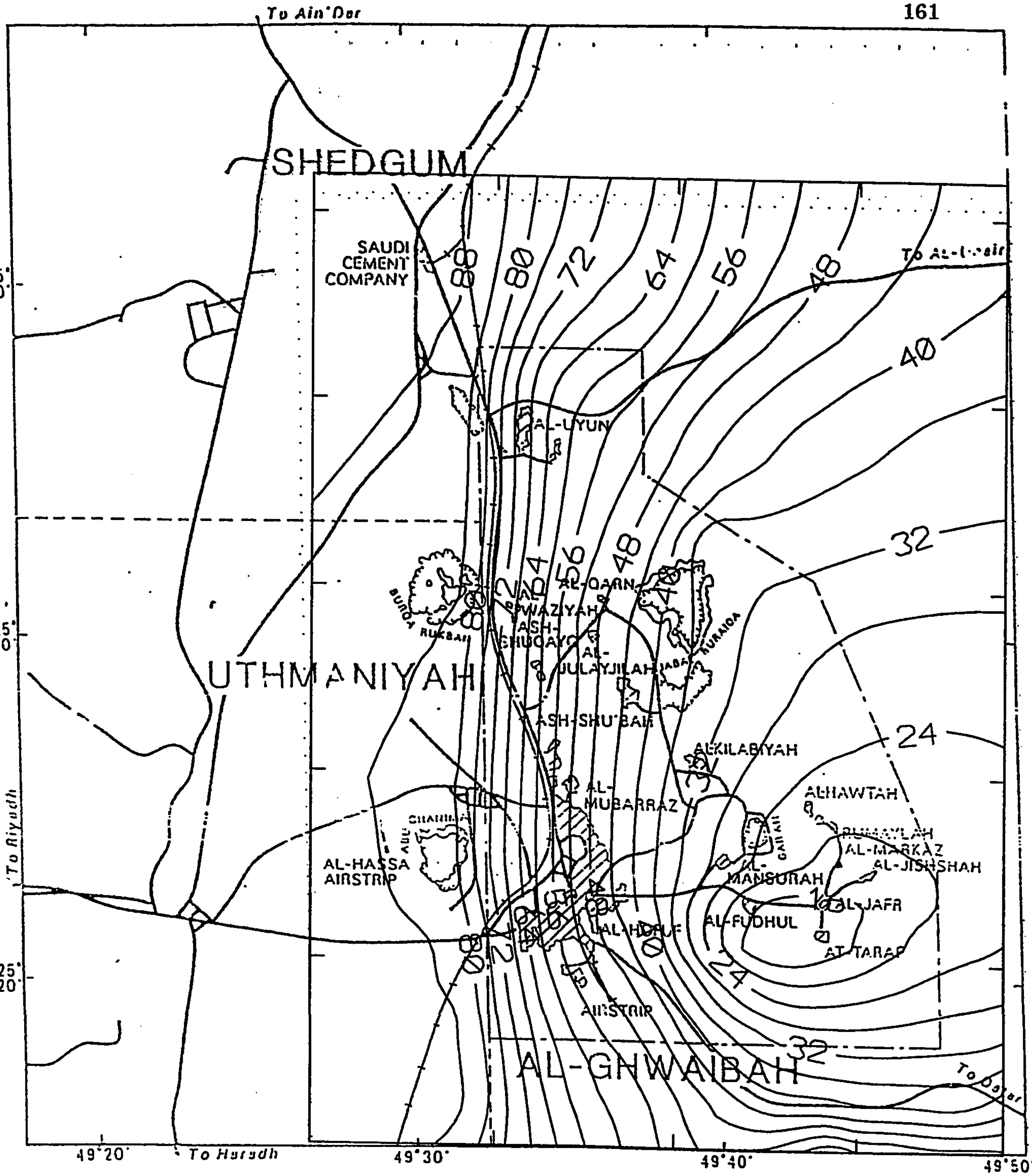


Figure 6.6 Predicted Heads with 29% Reduction in Pumping in Khobar-Alat Aquifer

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

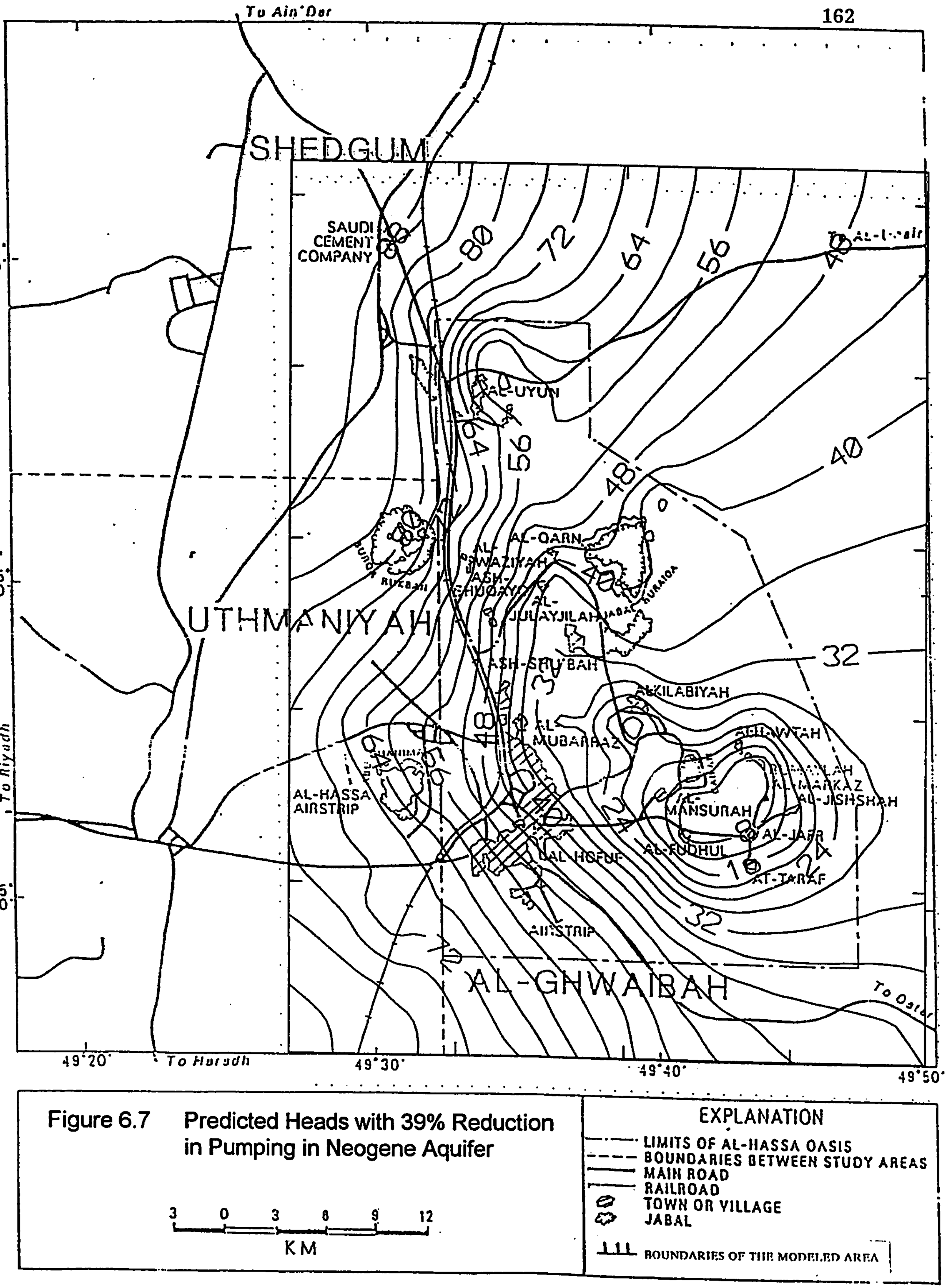


Figure 6.7 Predicted Heads with 39% Reduction in Pumping in Neogene Aquifer

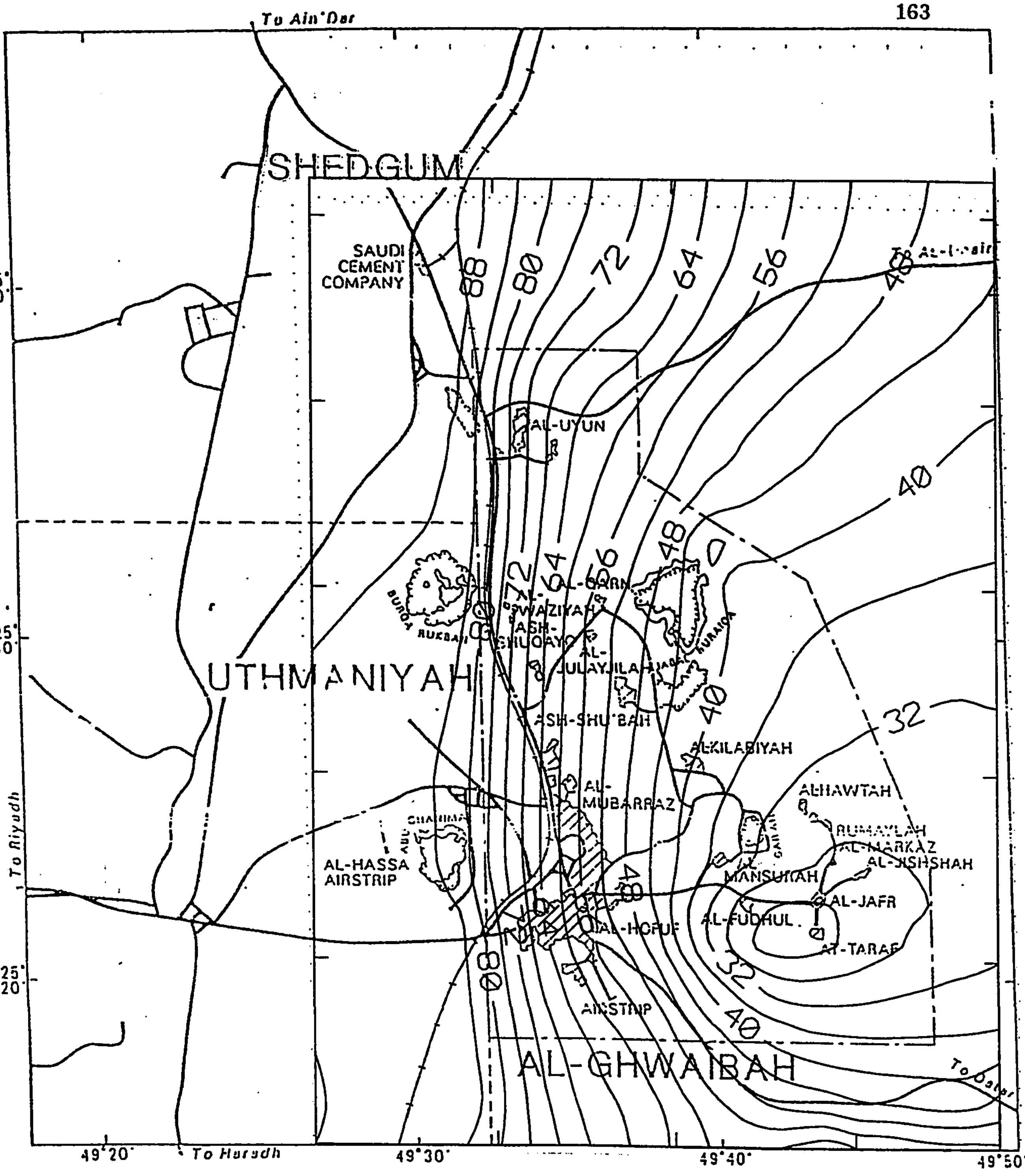


Figure 6.8 Predicted Heads with 39% Reduction in Pumping in Khobar-Alat Aquifer

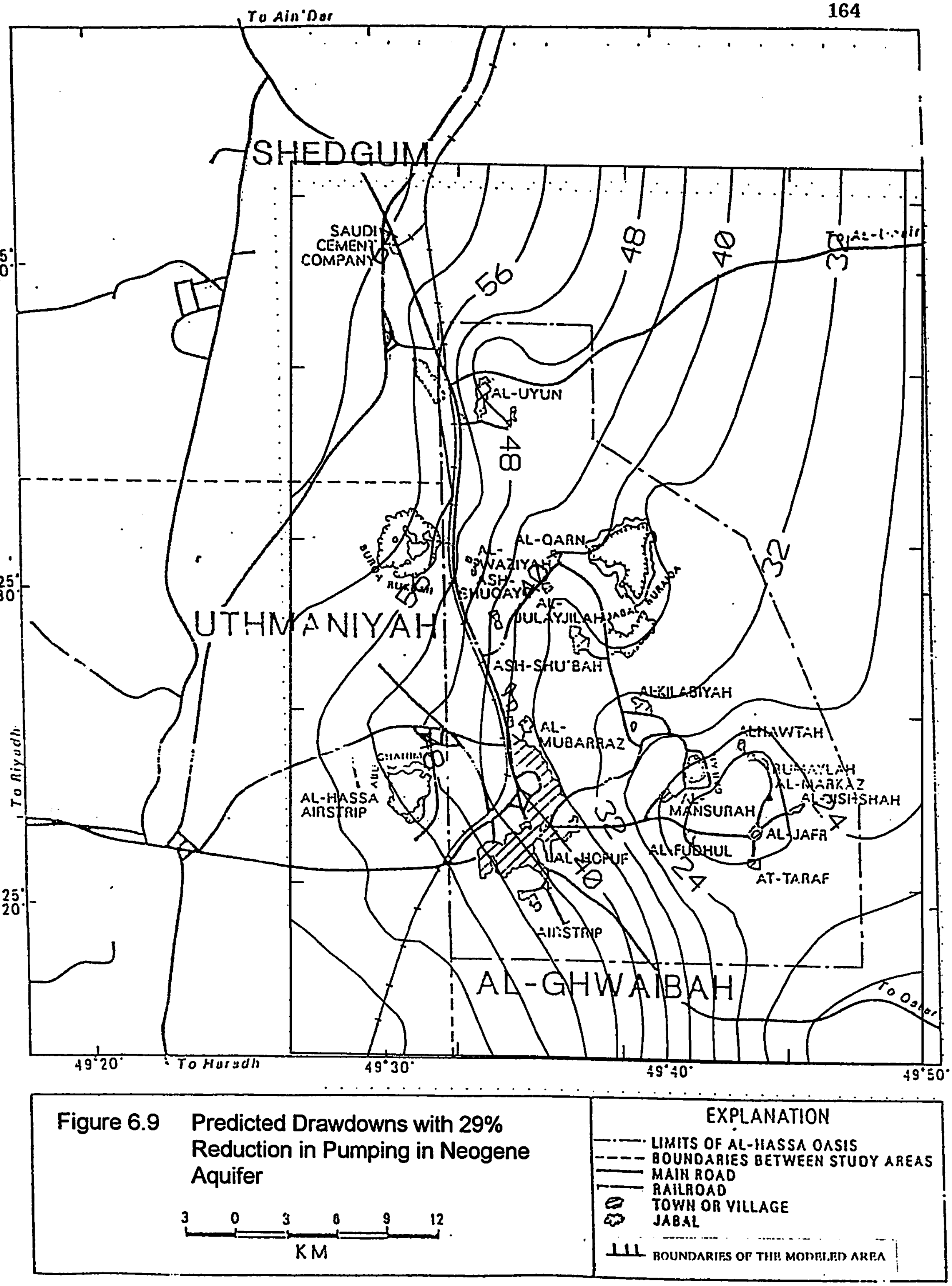


Figure 6.9 Predicted Drawdowns with 29% Reduction in Pumping in Neogene Aquifer

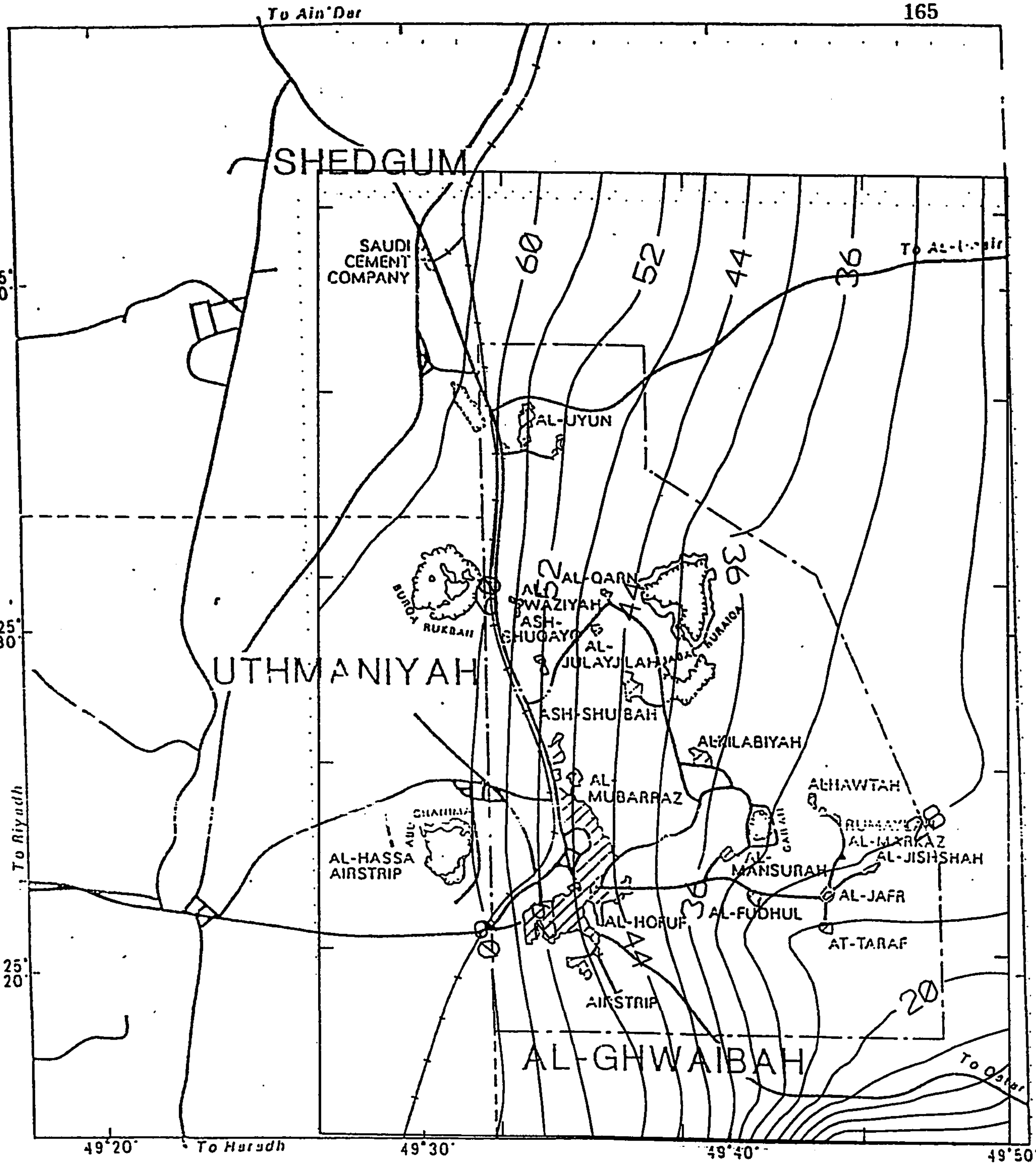


Figure 6.10 Predicted Drawdowns with 29% Reduction in Pumping in Khobar-Alat Aquifer

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

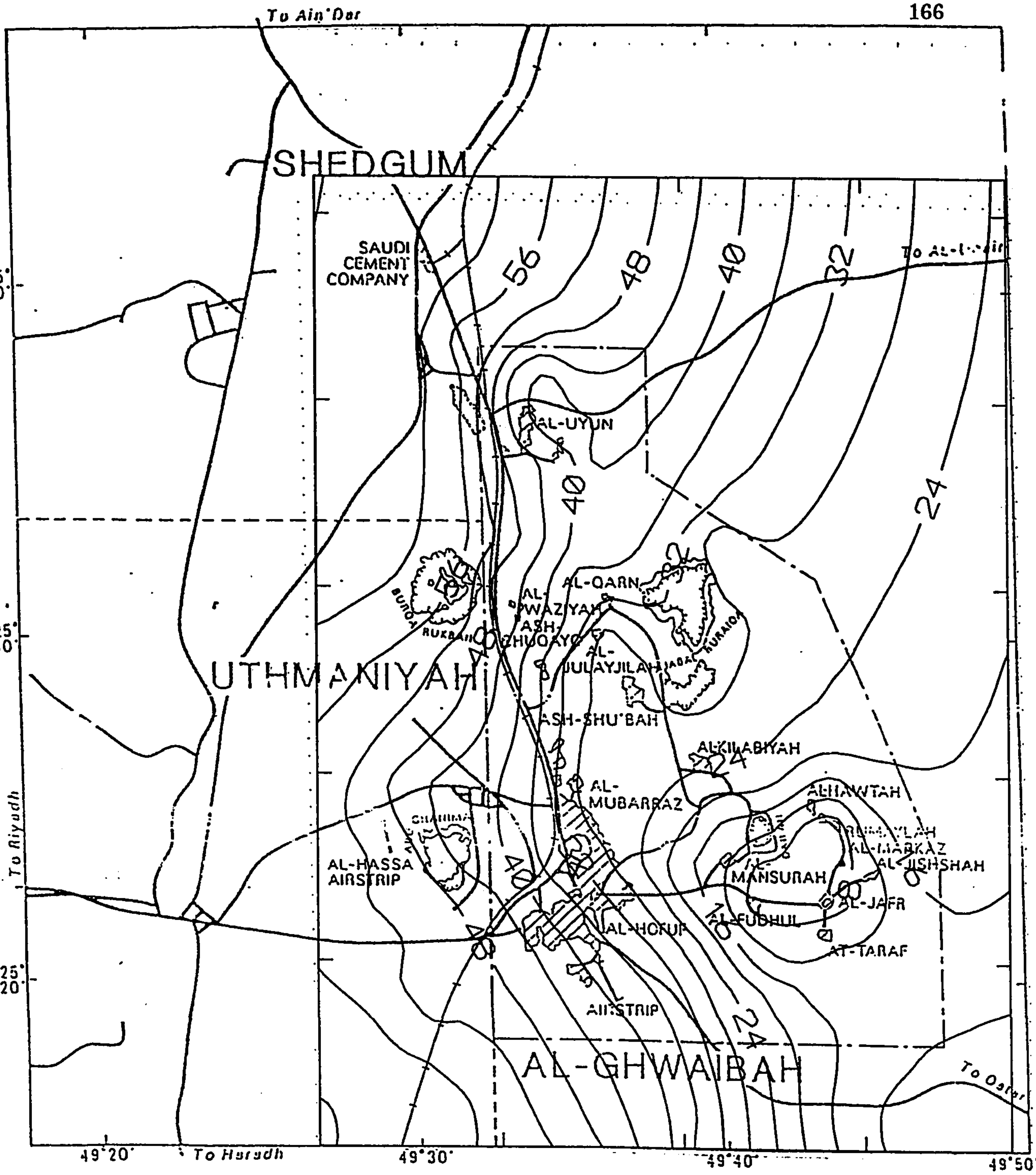


Figure 6.11 Predicted Drawdowns with 39% Reduction in Pumping in Neogene Aquifer

3 0 3 6 9 12
KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

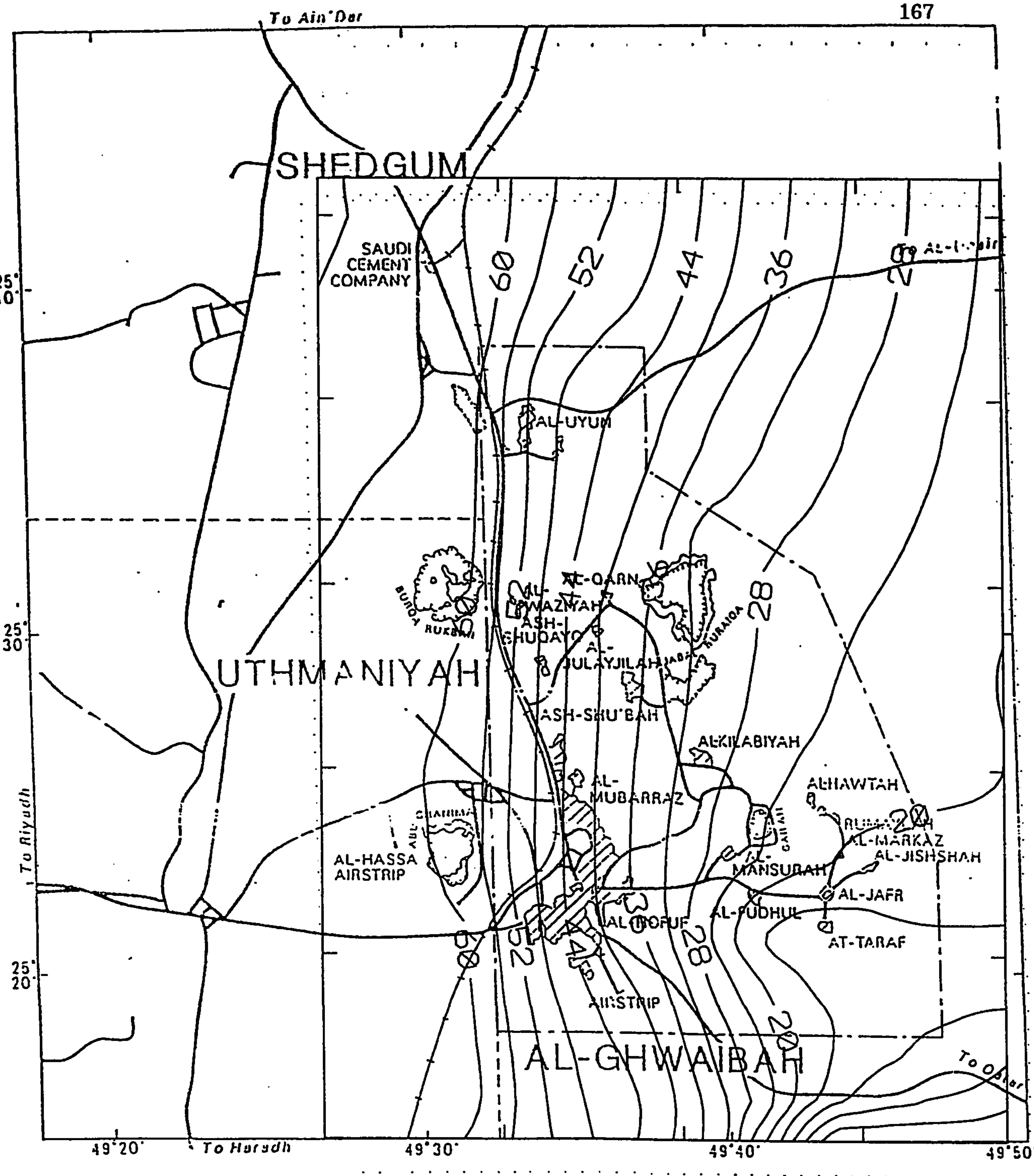


Figure 6.12 Predicted Drawdowns with 39% Reduction in Pumping in Khobar-Alat Aquifer

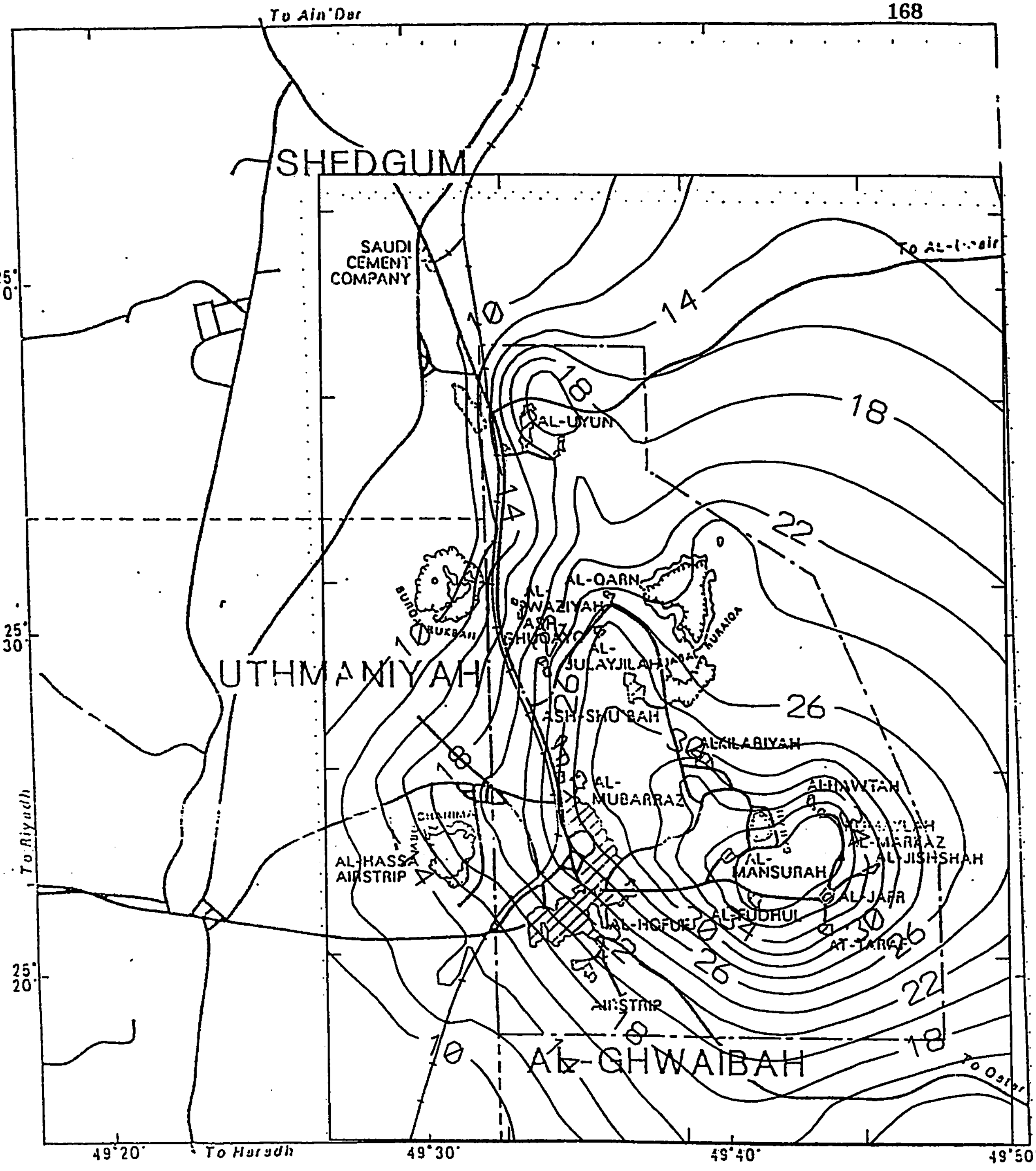


Figure 6.13 Heads Saved by 29% Reduction in Pumping in Neogene Aquifer

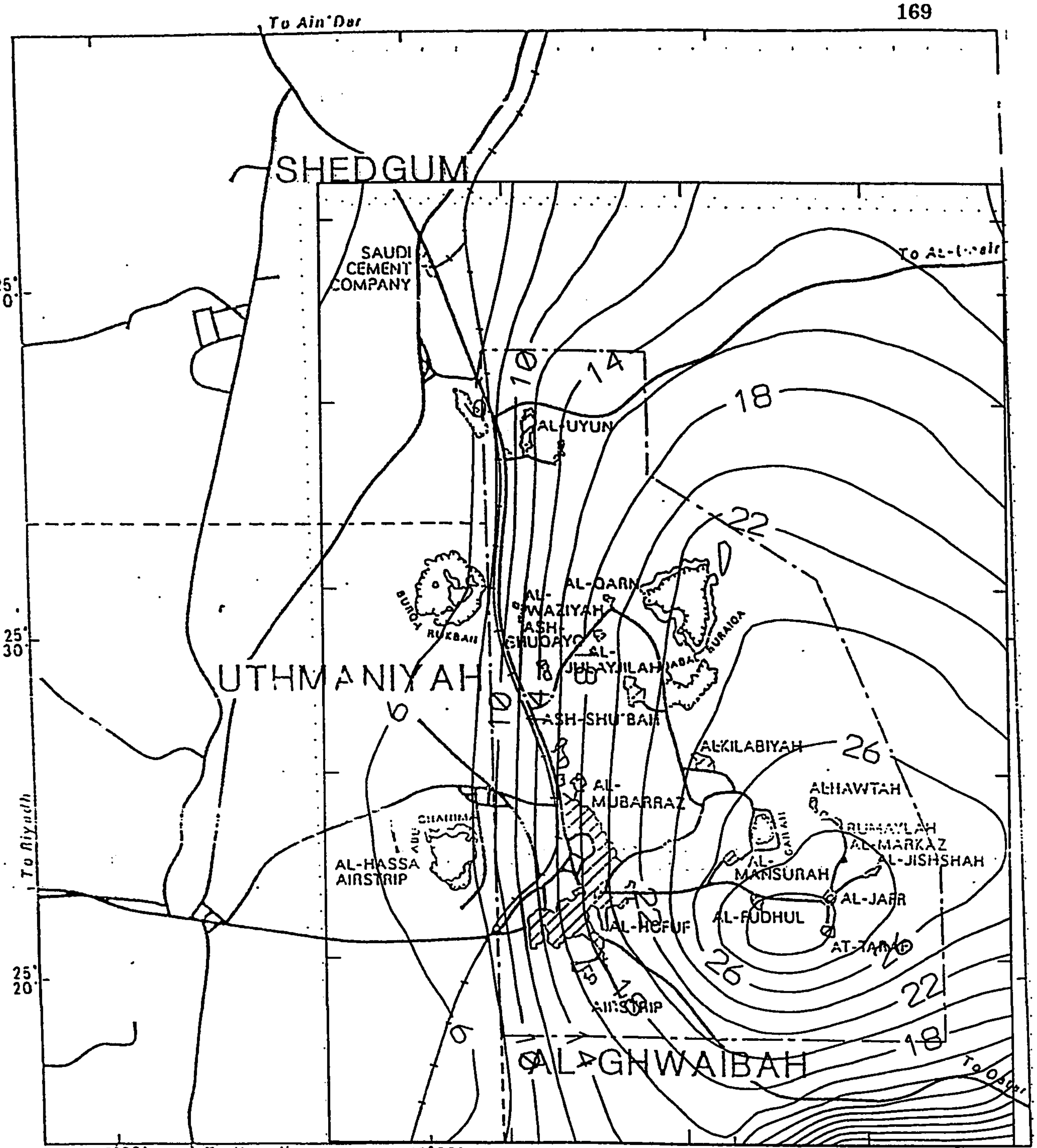


Figure 6.14 Heads Saved by 29% Reduction in Pumping in Khobar-Alat Aquifer

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

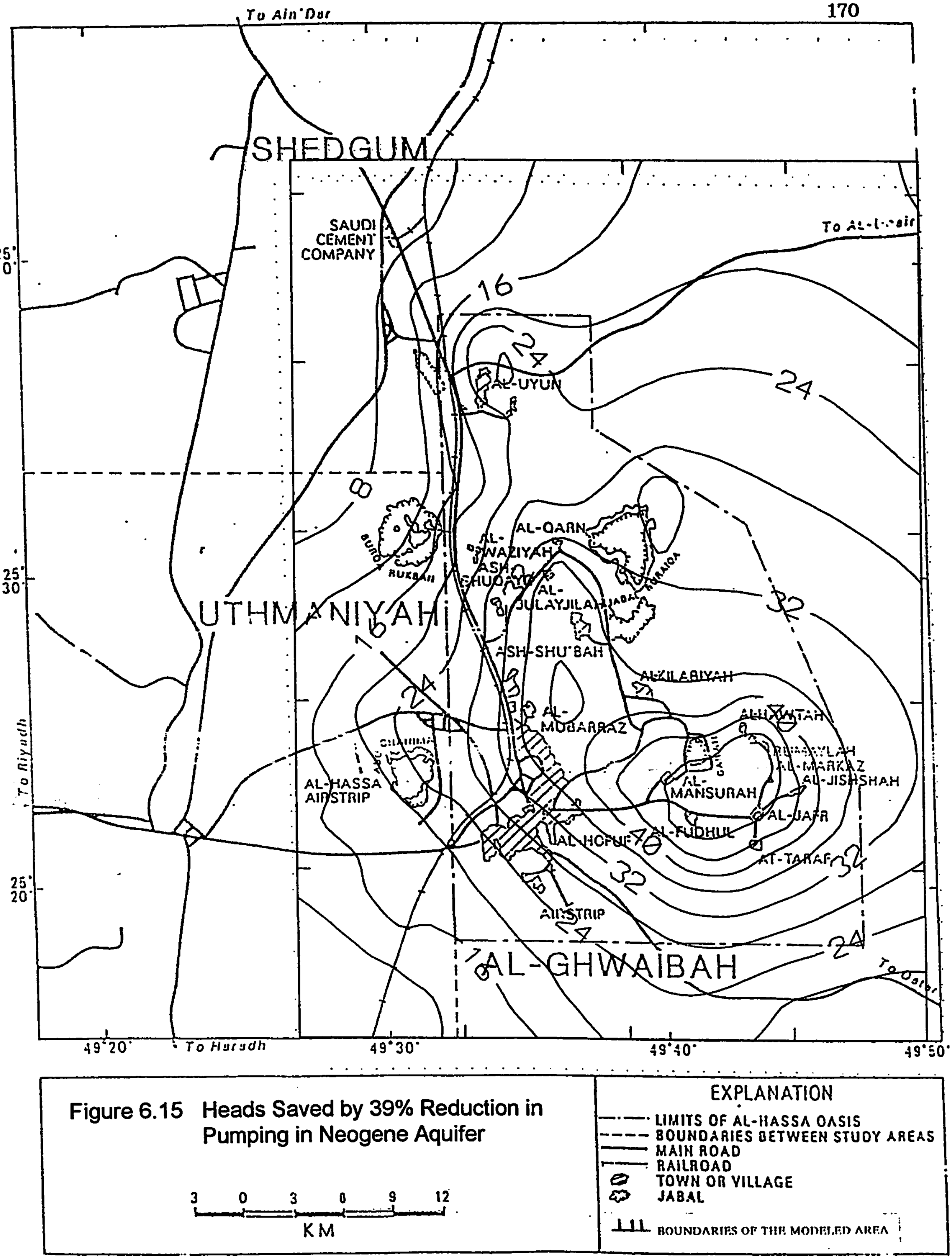


Figure 6.15 Heads Saved by 39% Reduction in Pumping in Neogene Aquifer

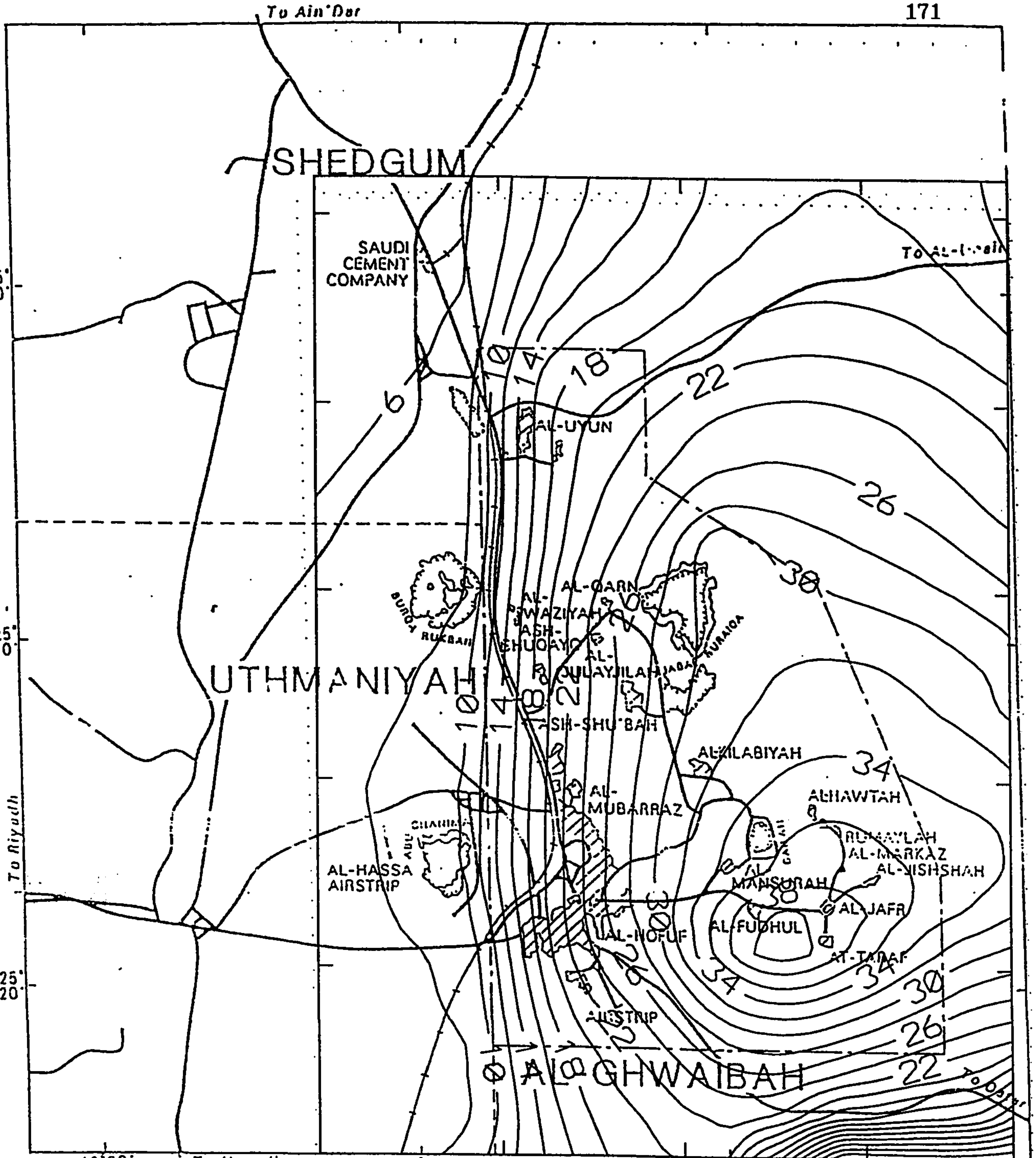


Figure 6.16 Heads Saved by 39% Reduction in Pumping in Khobar-Alat Aquifer

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

This saved head is obviously maximum at the heavily pumped area (the southern central portion of the study area). With 29 % lowering in pumpage, more than 6 meters of head is saved at the southern central portion of Al-Hasa Oasis. Head saving in the case of 39 % pumpage reduction is about 8 meters at that particular place. However, with 29 % as well as with 39 %, the difference becomes negligible as it marches to the boundaries.

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7. 1 Conclusions

- The geology and hydrogeology of the study area were studied in detail. The geology of the area has a great impact on the hydrogeological parameters of the study area. The Neogene aquifer is not hydrologically independent of underlying water-bearing formations. Alat and Khobar aquifers have direct contact with both the underlying Umm er Radhuma and the overlying Neogene aquifers. In all probability, this implies that any increased pumping from the Neogene or any other aquifer in Al-Hasa would affect the whole hydrological system of the Oasis.

- Al-Hasa springs derive their water from the Neogene aquifer complex through numerous fractures in the impervious overlying strata. Such fractures permit the confined water under hydrostatic pressure to emerge above the ground surface as free flowing springs.

- It is hydrologically found that most of Al-Hasa springs are interconnected by a network of tunnels. This means that excessive withdrawal from some springs would reduce the natural discharge rate from the others.

- A quasi-three dimensional finite difference model was used to simulate the groundwater depletion in Al-Hasa area. The model was calibrated against measured values of heads at different locations and various time horizons in the study area. The model showed good agreement between measured and simulated heads with the difference hardly exceeding few meters.

- Only the Khobar-Alat and the Neogene aquifers were simulated. This was decided after a complete simulation of the three aquifers where the results showed that the UER aquifer can be replaced by a reasonable vertical leakance.

- With reference to the year 1983/84, with no change in the present discharge pattern, a huge drawdown is expected to prevail in 1996/97. This drawdown is expected to take place at the rate of about 5 meters/year.

- Two alternatives were considered: the no growth alternative and the conservation one (reduction in consumed water), with a planning interval of five years for each. The no growth option showed that a cone of depression remained to be in the south middle part of the study area.

- Conservation is attainable via utilizing properly treated sewage effluent, agricultural drainage water, and automation of Al-Hasa Irrigation and Drainage Project. The minimum expected saving in water demand is about 29% and it can reach as high as 39%. The simulation runs have shown a remarkable saving in heads especially at the locality of the depression cone.

7. 2 Recommendations

- A high depletion rate is noticed. The water level is expected to fall at the rate of 5 meters/year. A very strict conservation scheme should be adopted to maintain the drawdowns to a minimum.

- If conservation is not possible, other sources should be used as to limit the need for groundwater which is a finite source with limited recharge. One source of potential interest is the secondary effluent from treatment plants.

- Al-Hasa irrigation project is operated manually. Automation, definitely helps to reduce water demand by eliminating the flow of excess water of certain canals, gates,...etc.

- The scarcity of data on well piezometric heads and discharge rates and the poor monitoring of the water levels make it necessary to adopt a major hydrogeological model especially designed for Al-Hasa in which a close monitoring on a daily basis is conducted.

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APPENDIX

Heads and Drawdowns in Neogene and Khobar-Alat Aquifers (1983-1996)

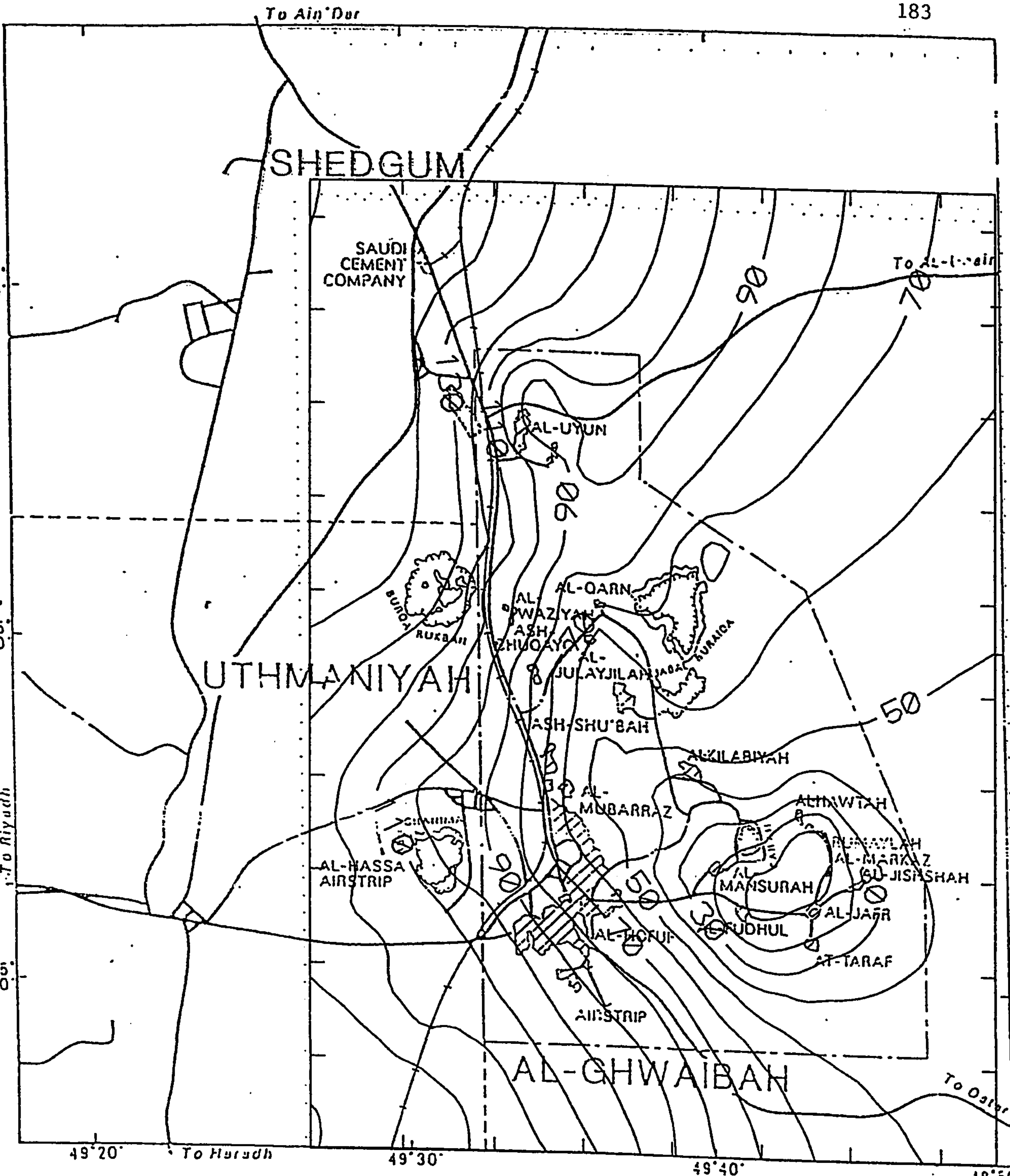


Figure A1 Heads in Neogene Aquifer/ Al-Hasa Oasis 1983/1984

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

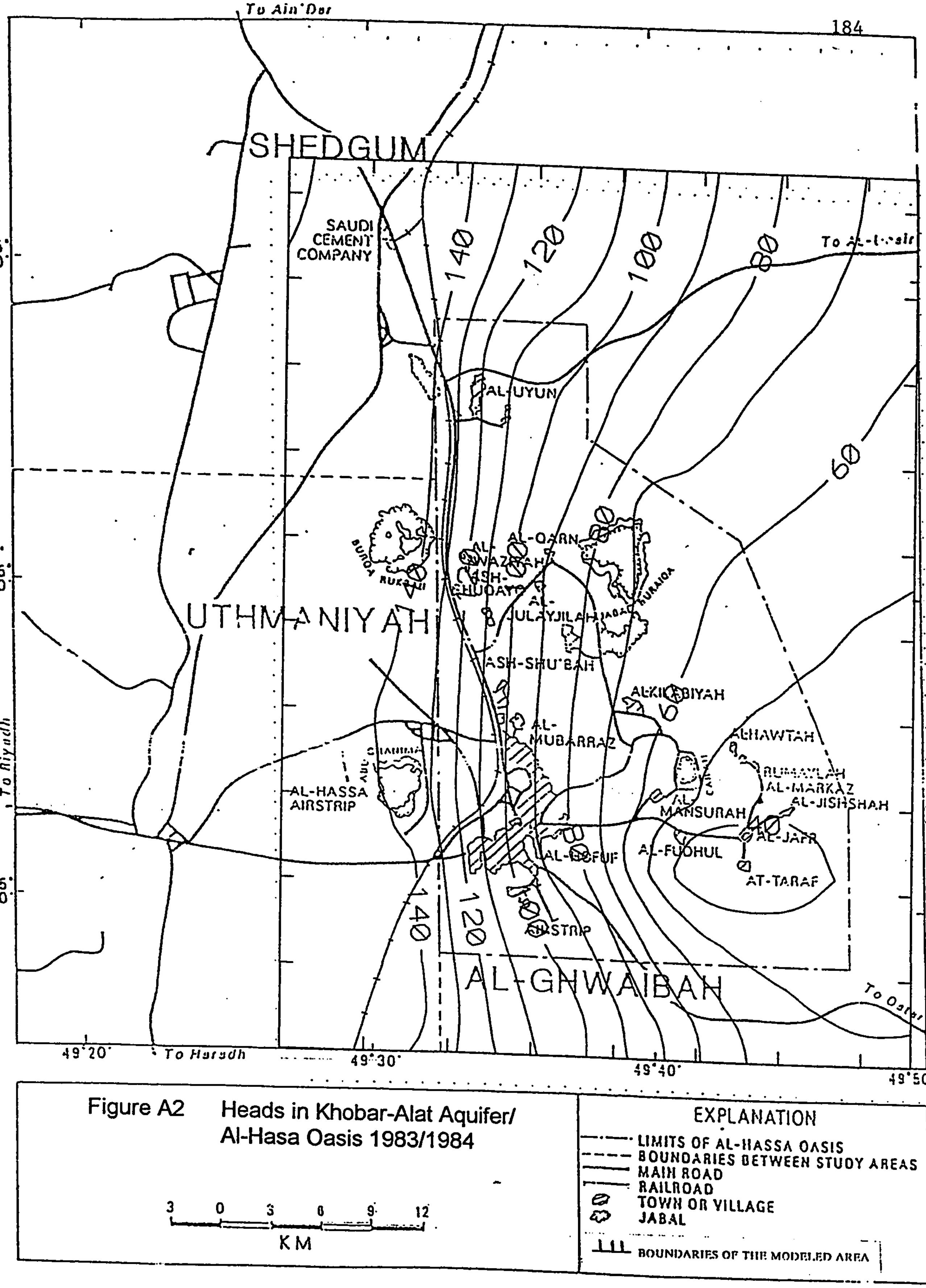


Figure A2 Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1983/1984

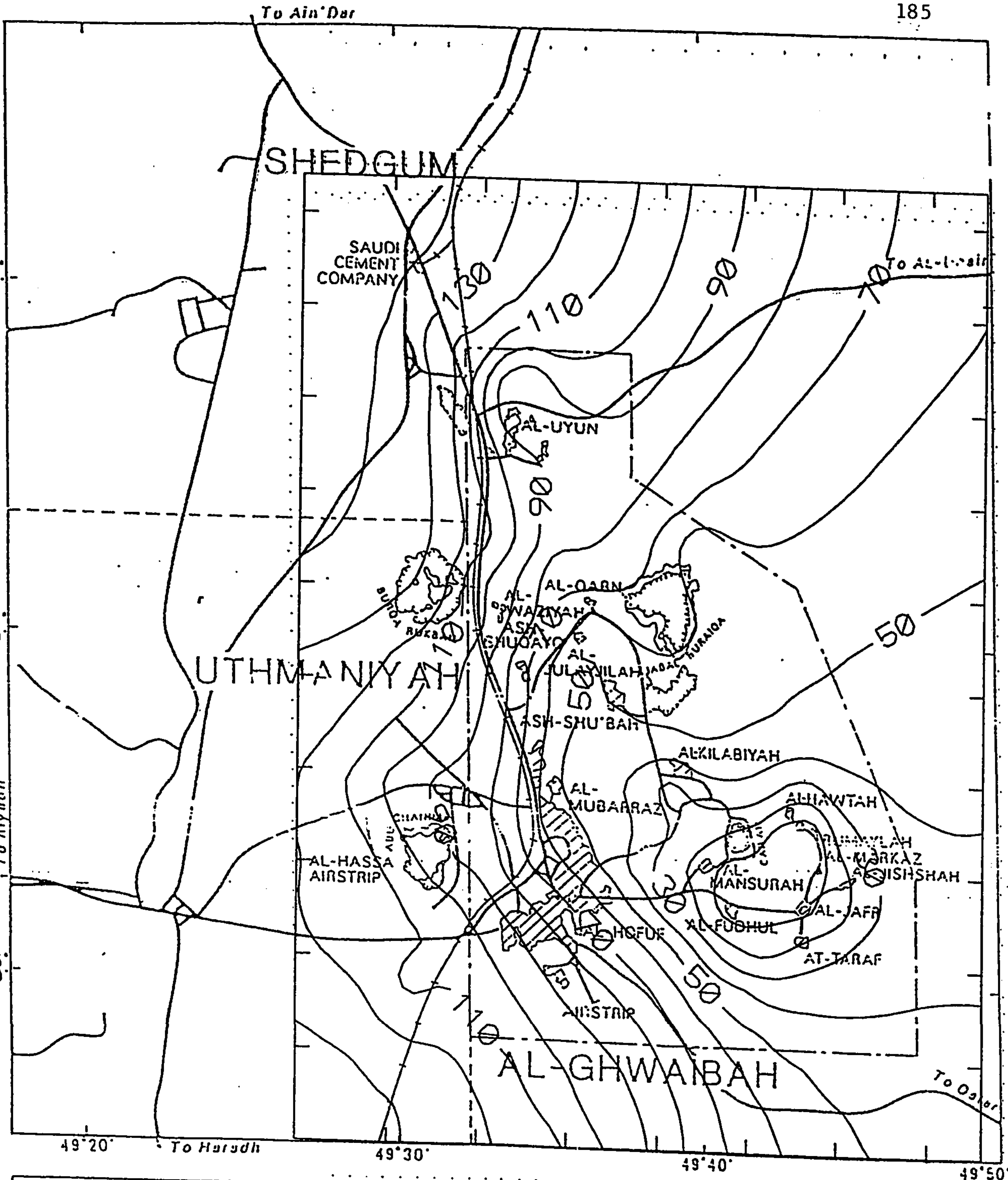


Figure A3 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1984/1985

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

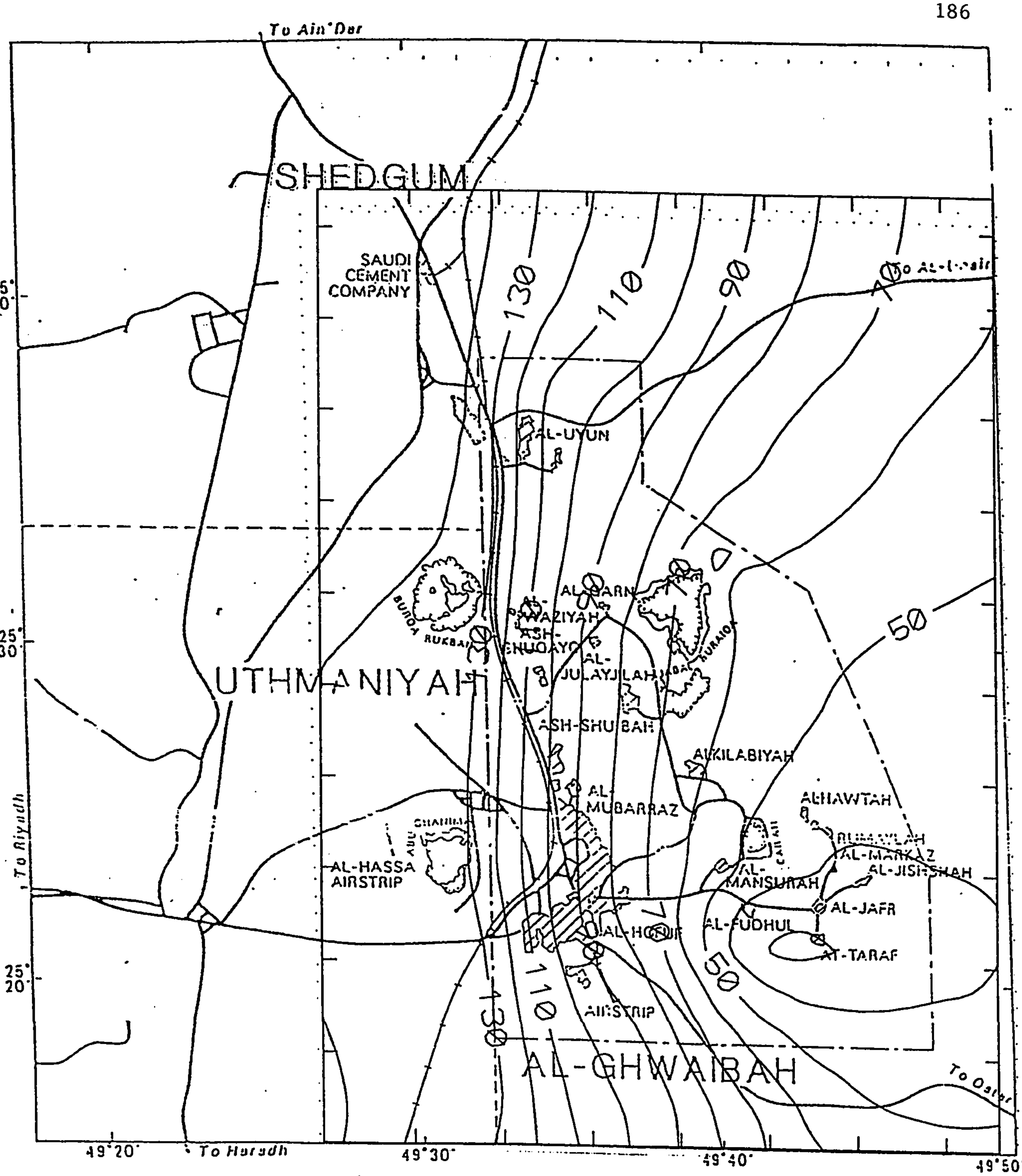


Figure A4 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1984/1985

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

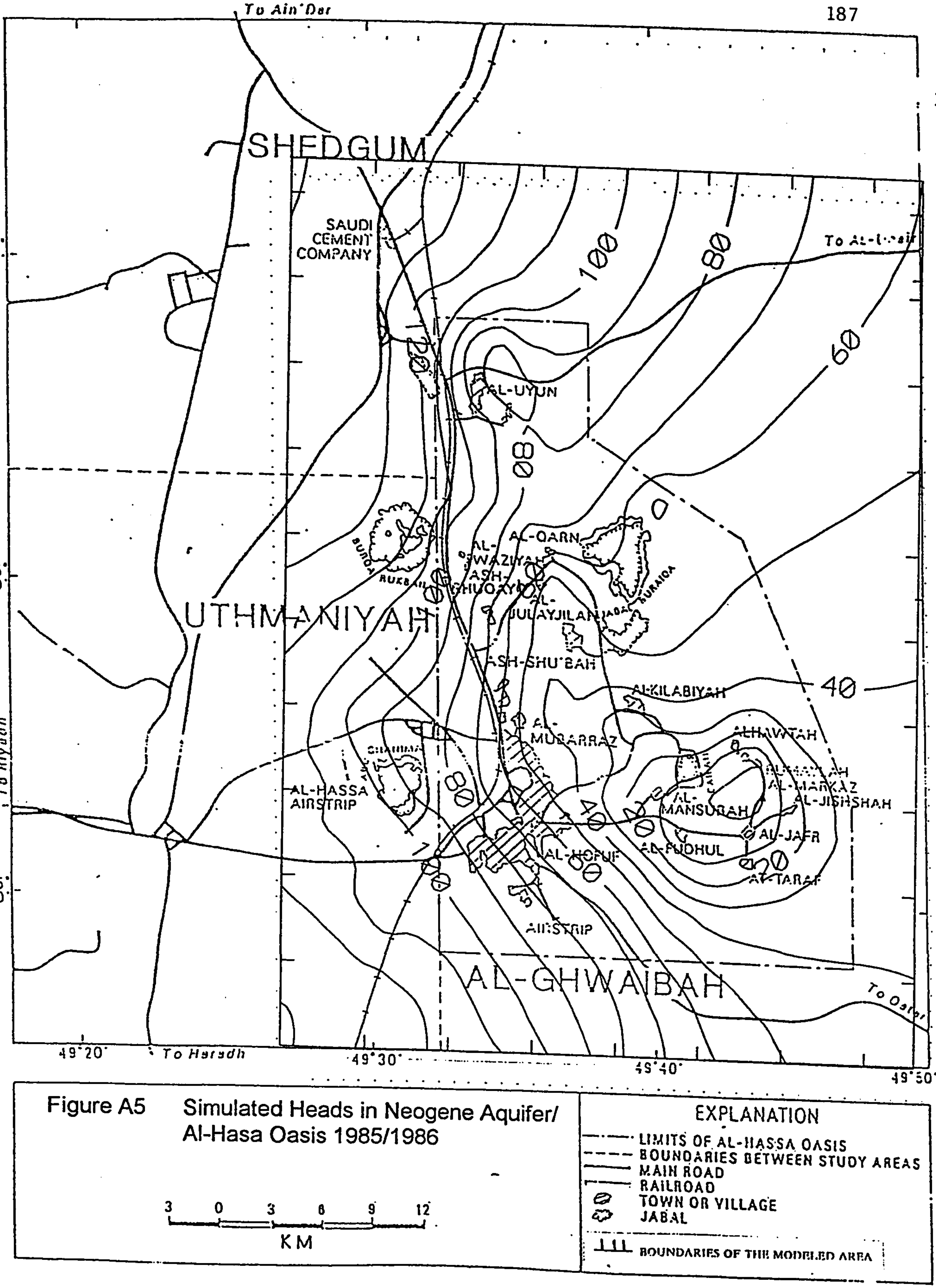


Figure A5 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1985/1986

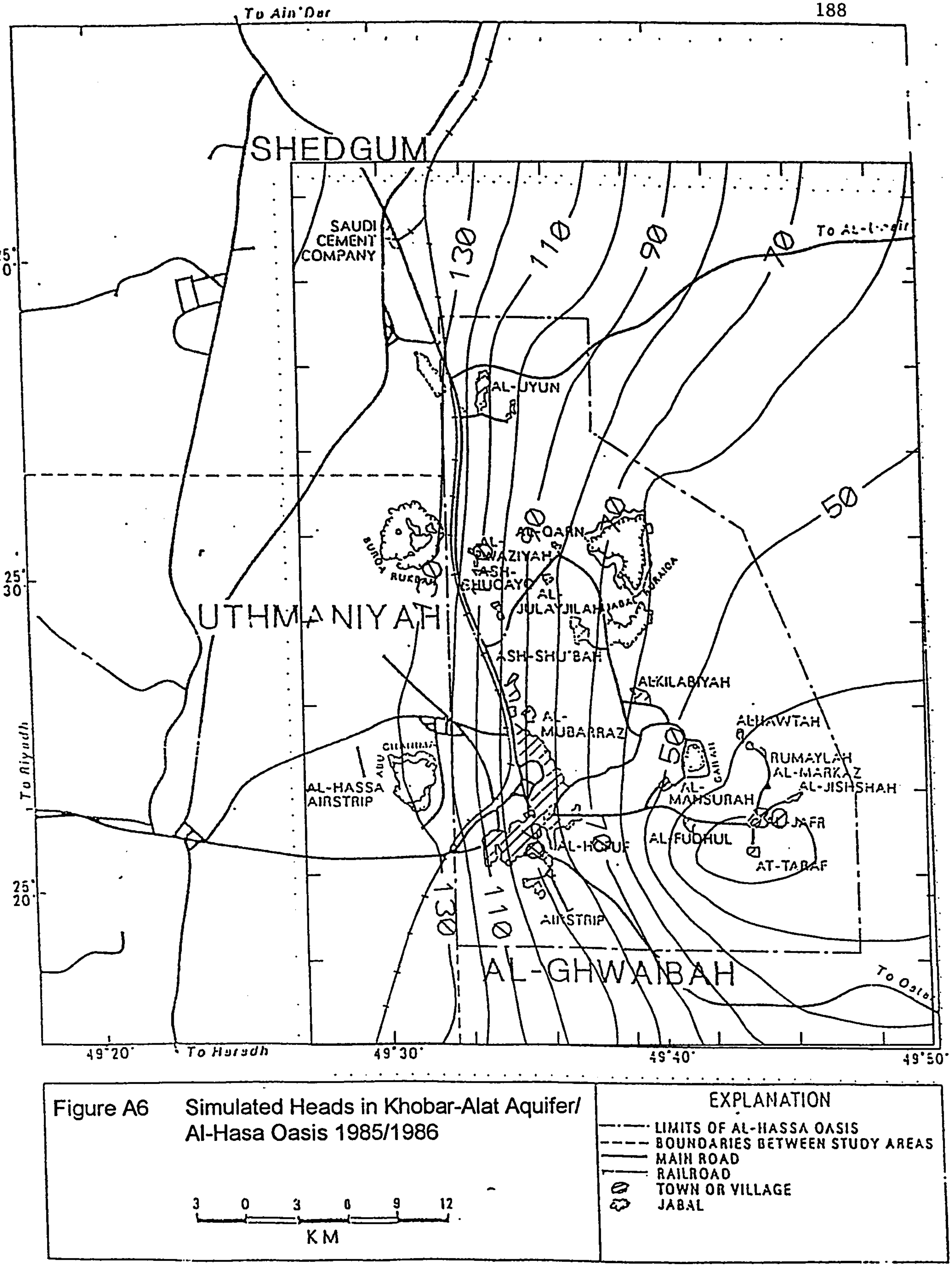


Figure A6 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1985/1986

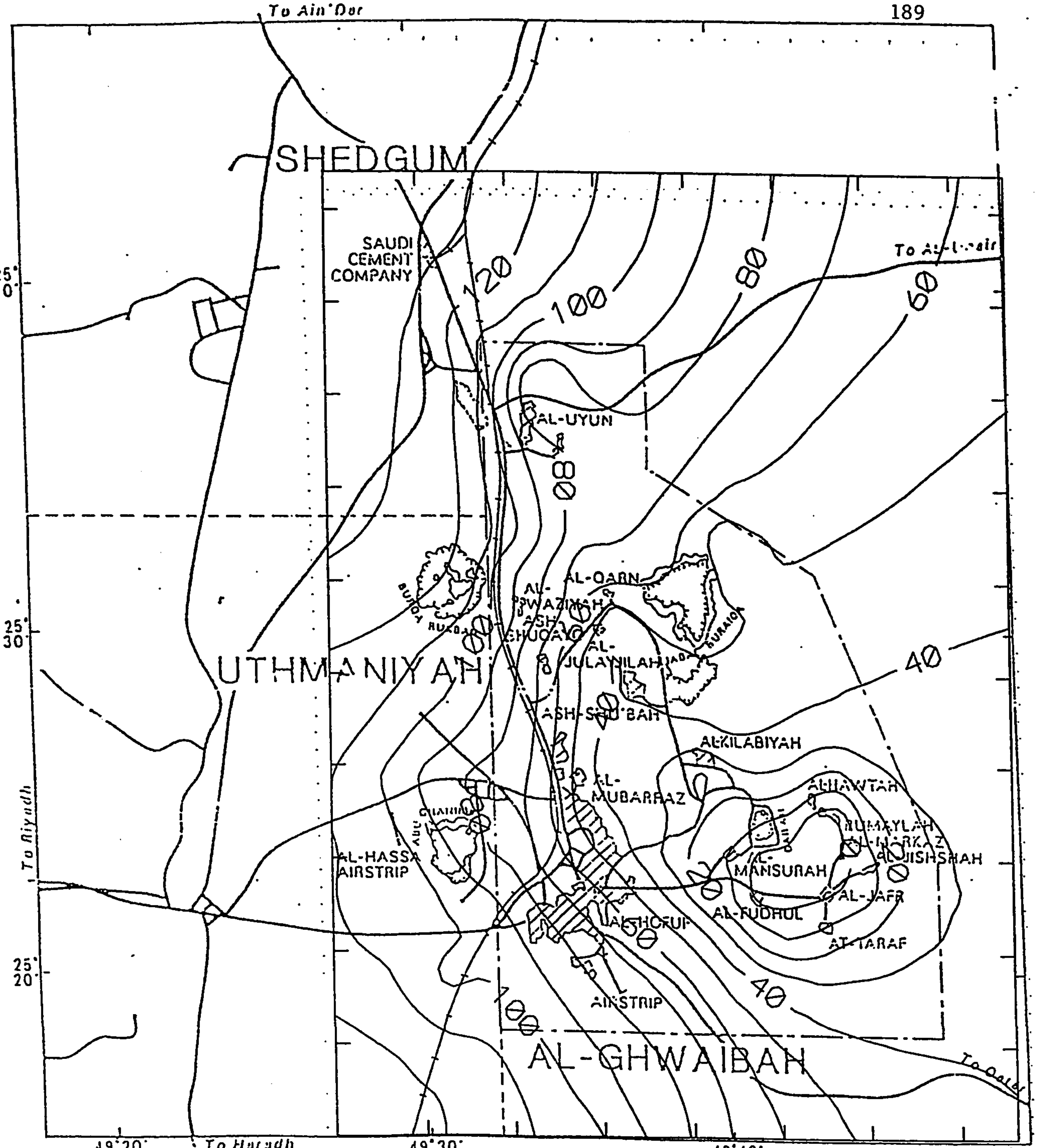
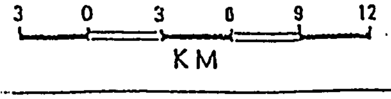


Figure A7 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1986/1987



EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL

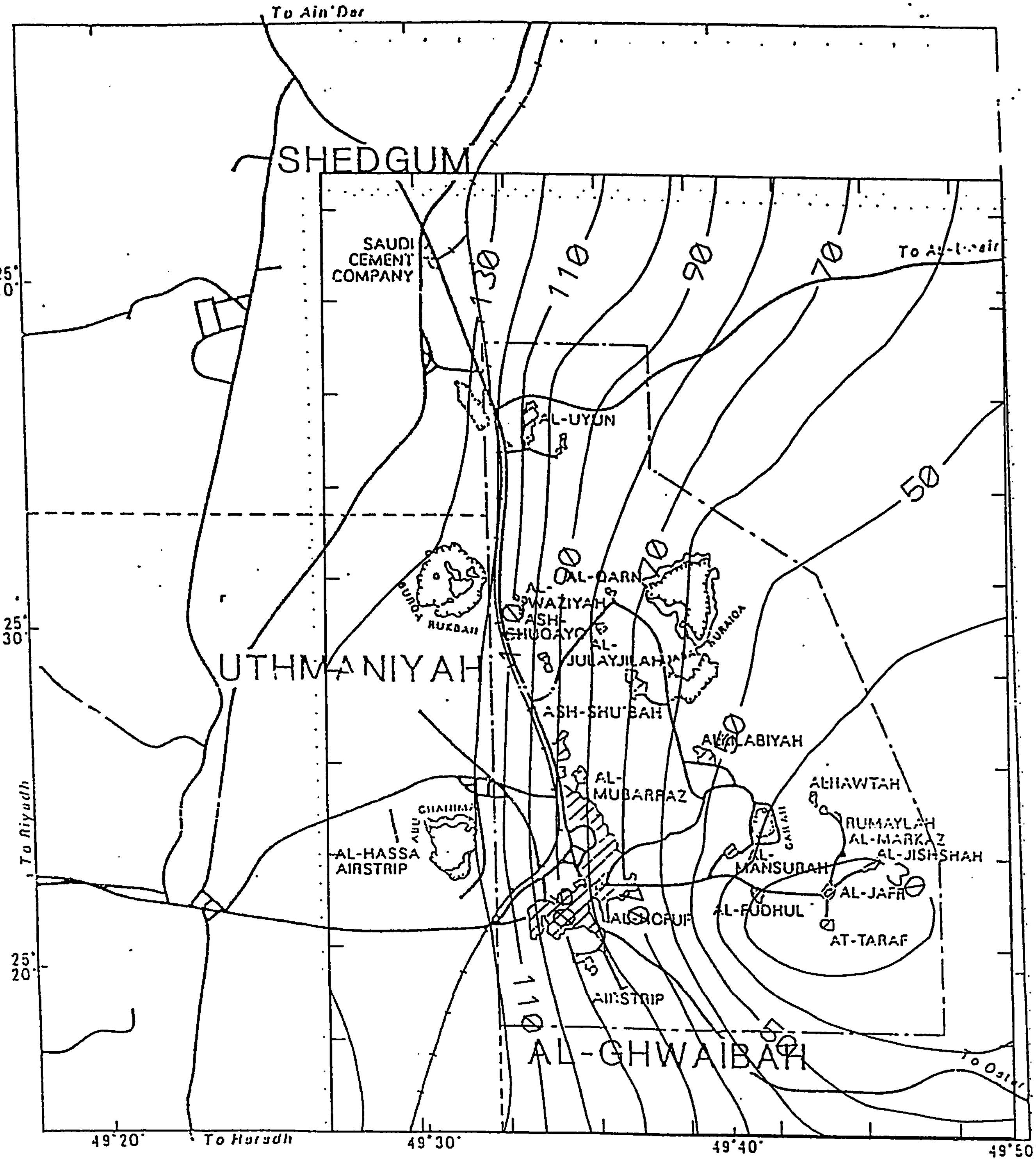


Figure A8 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1986/1987

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL

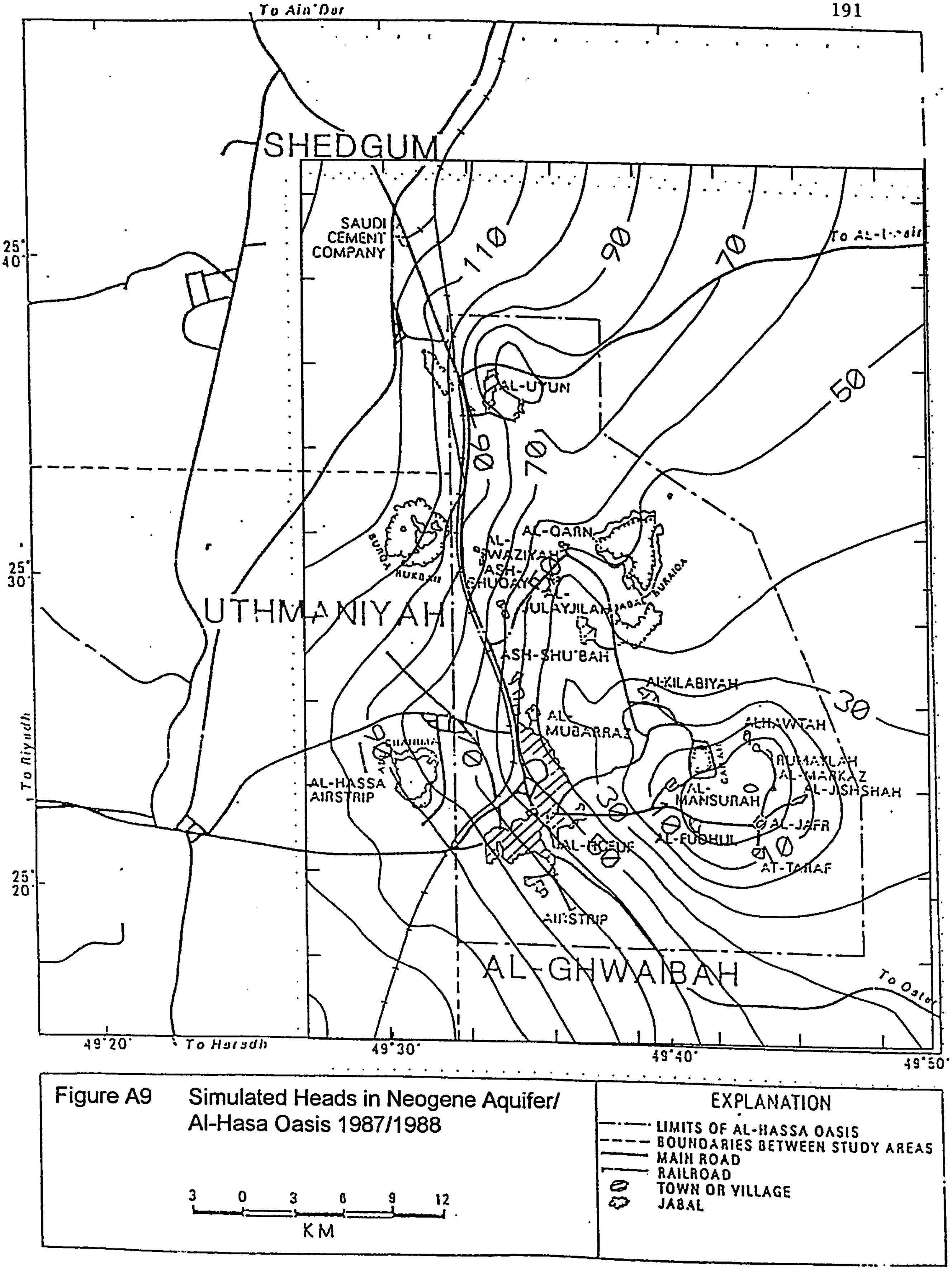


Figure A9 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1987/1988

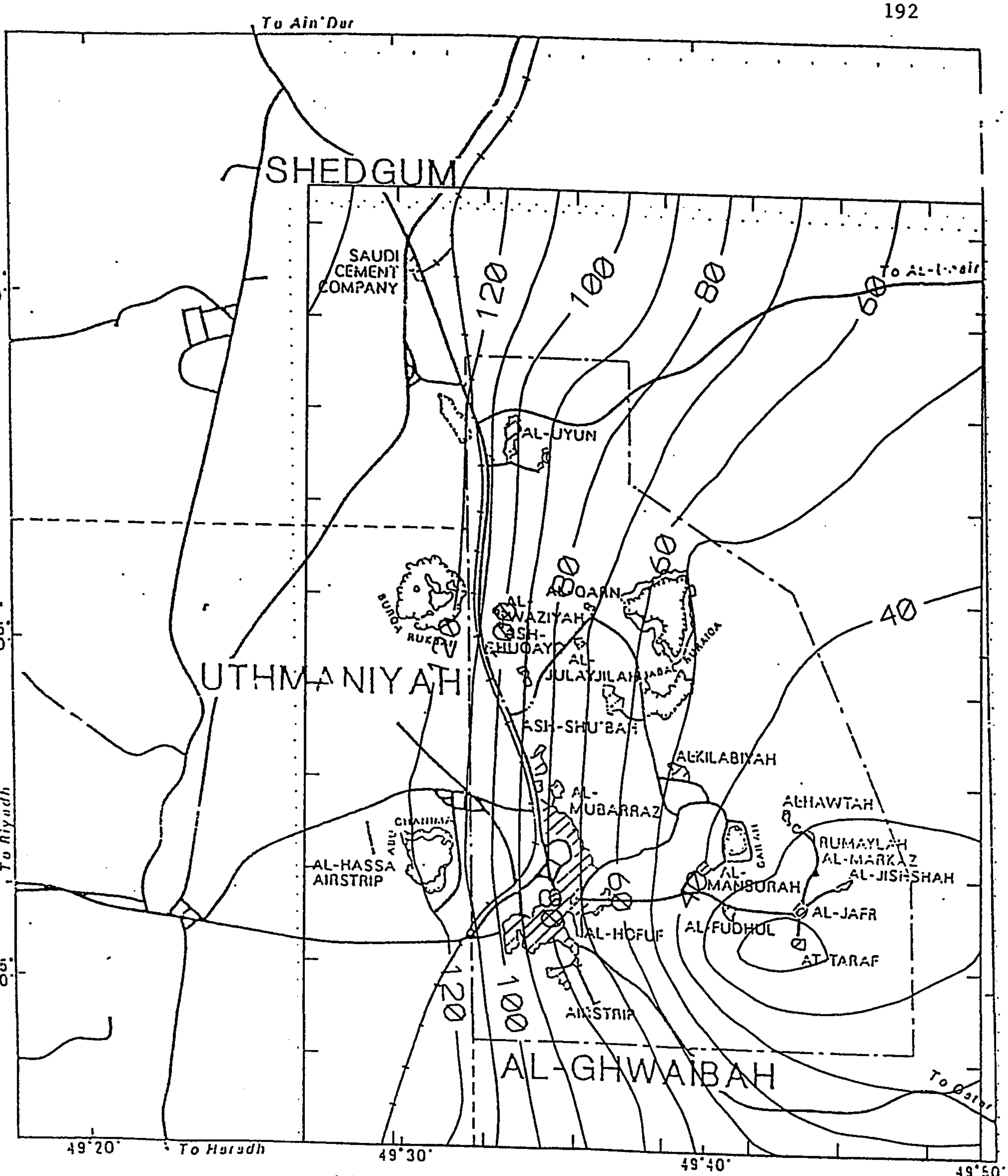


Figure A10 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1987/1988

3 0 3 6 9 12

KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL

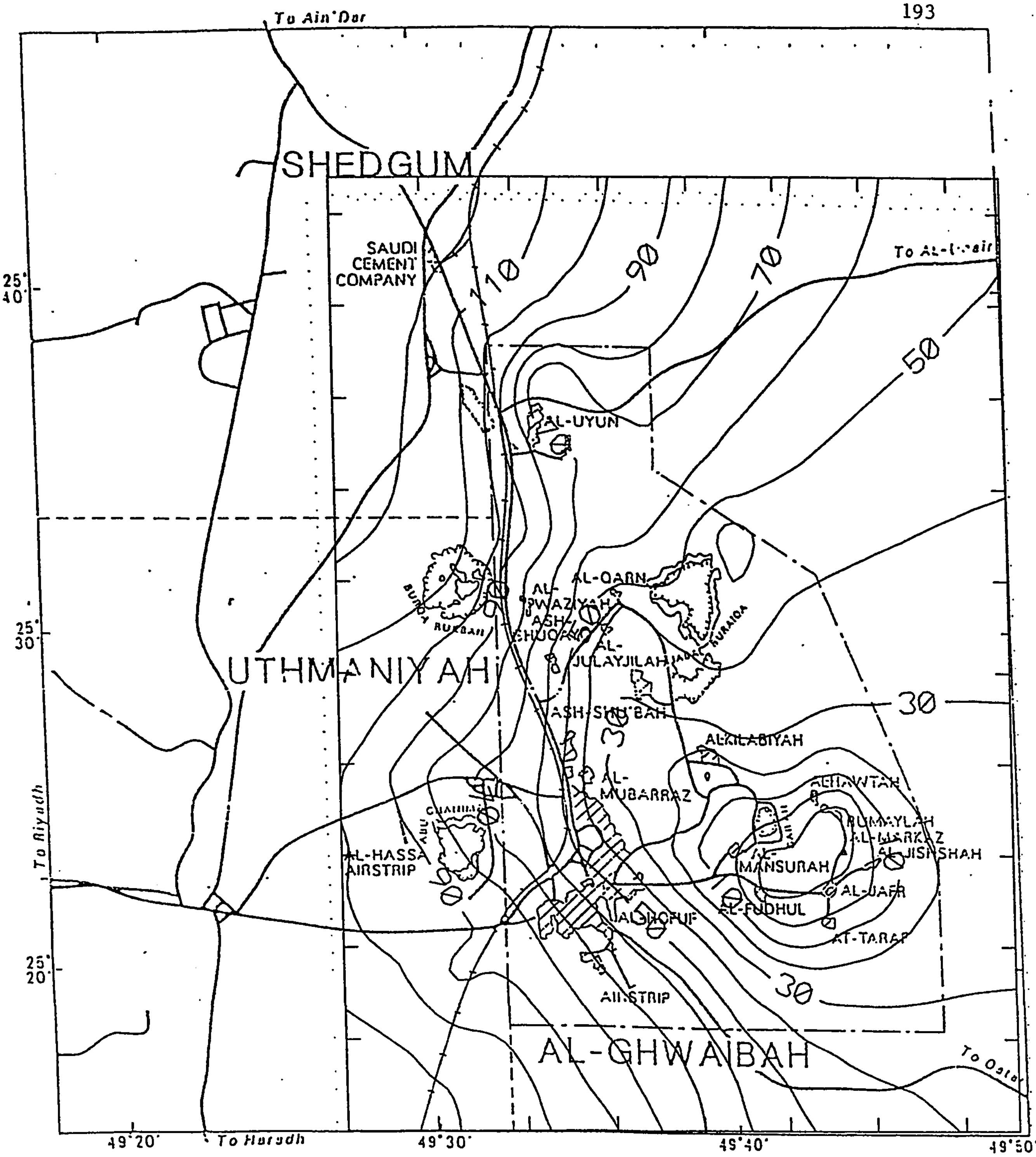


Figure A11 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1988/1989

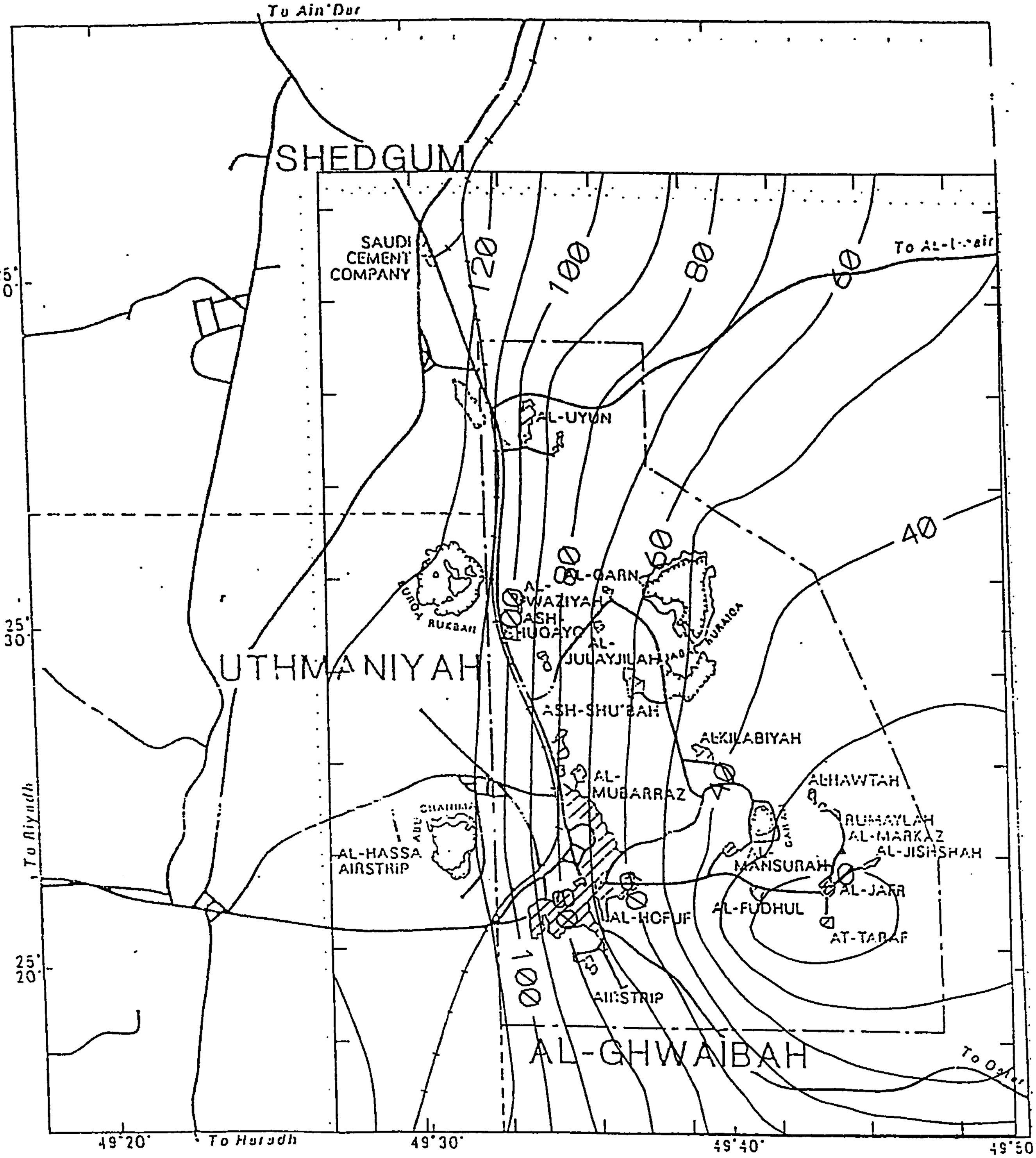


Figure A12 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1988/1989

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

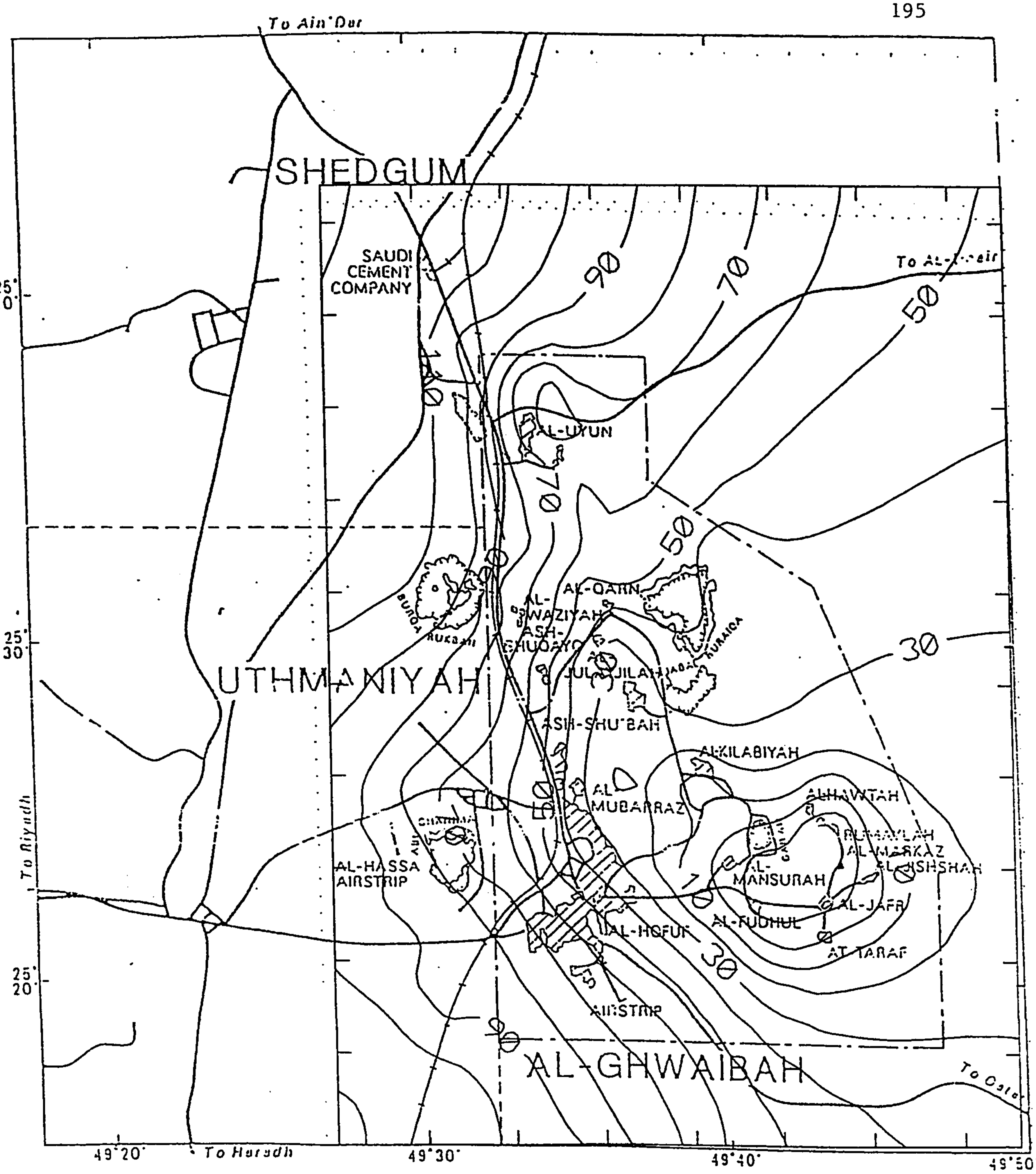


Figure A13 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1989/1990

3 0 3 6 9 12

KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

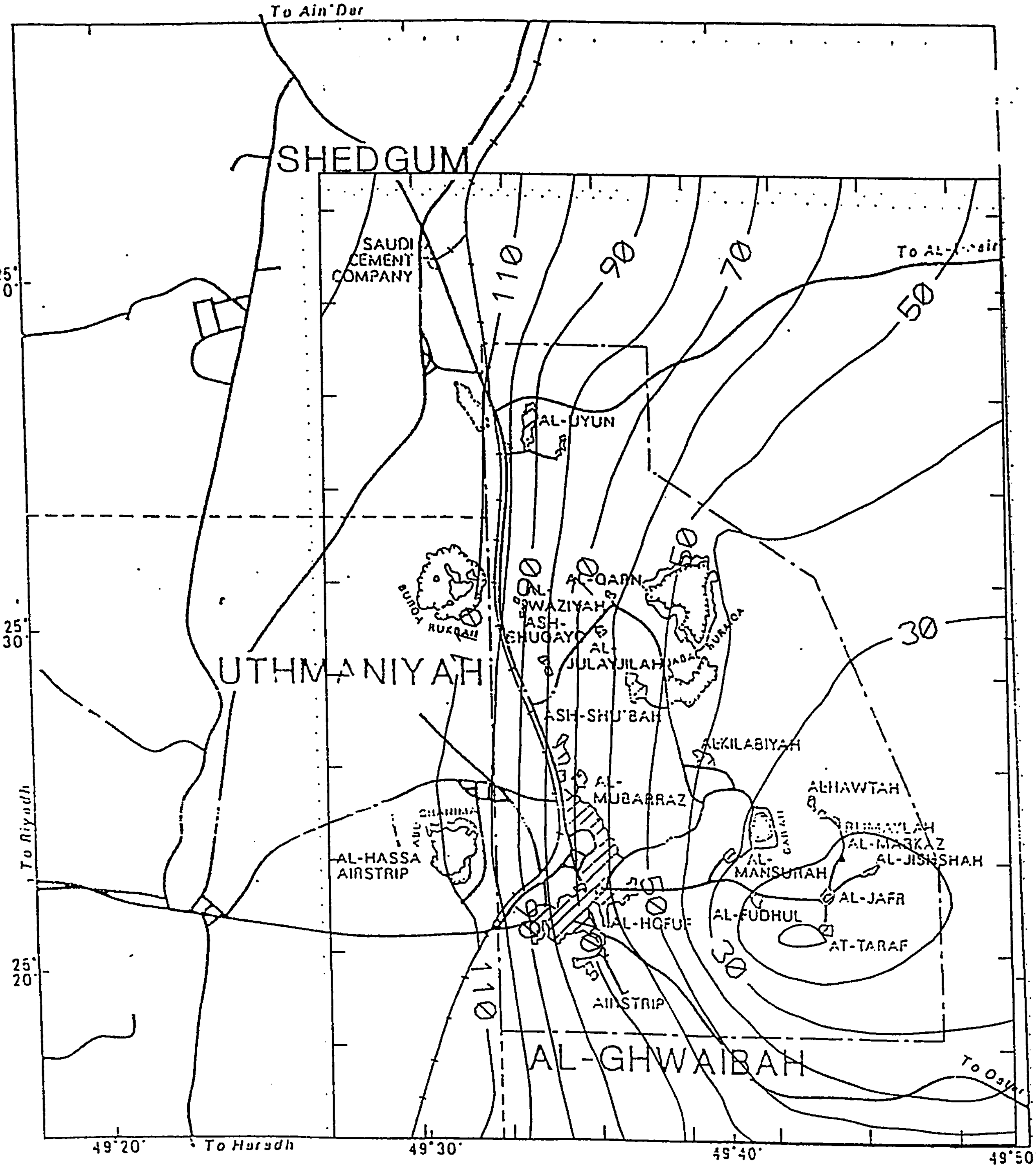


Figure A14 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1989/1990

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

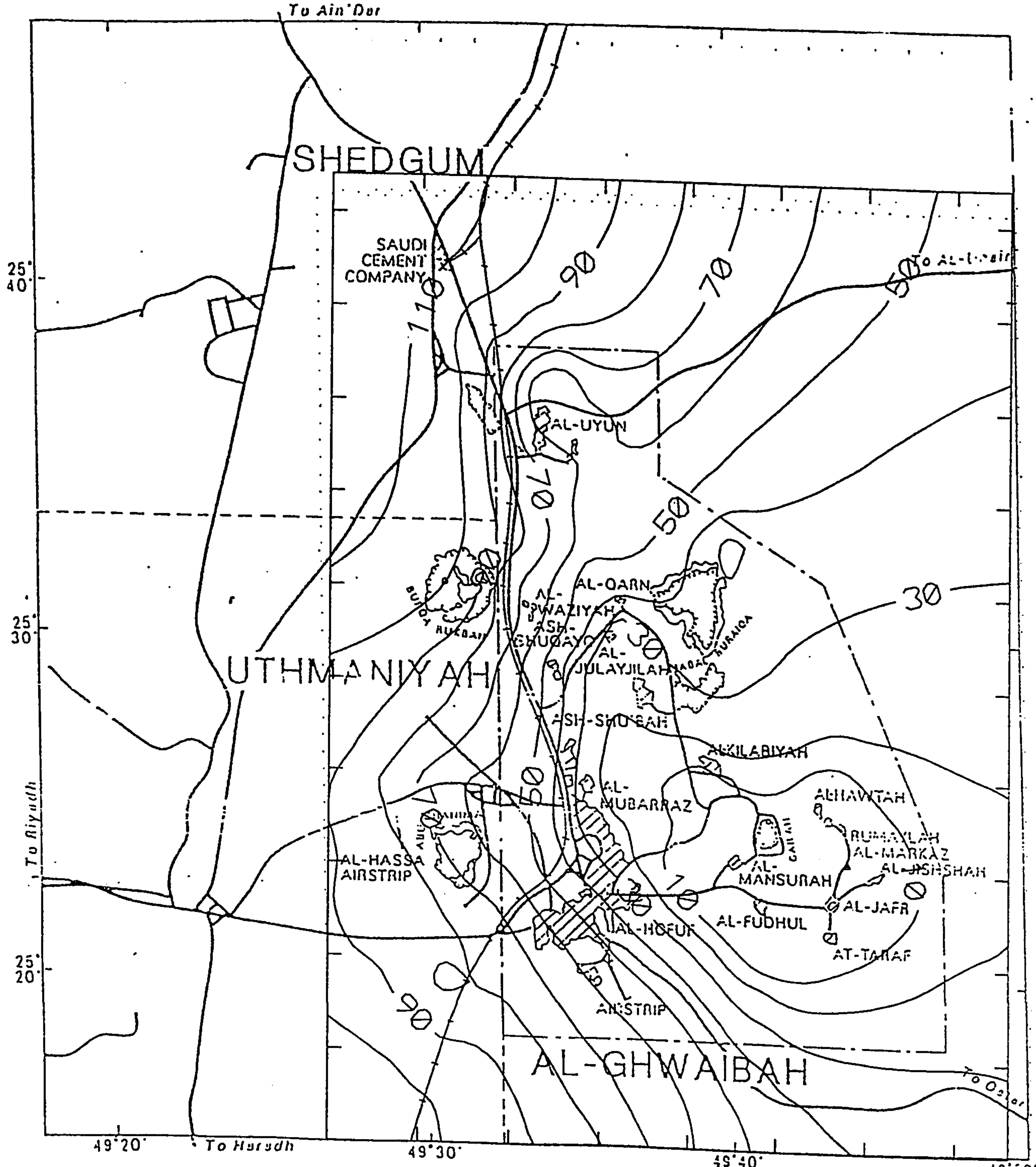


Figure A15 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1990/1991

3 0 3 6 9 12

KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

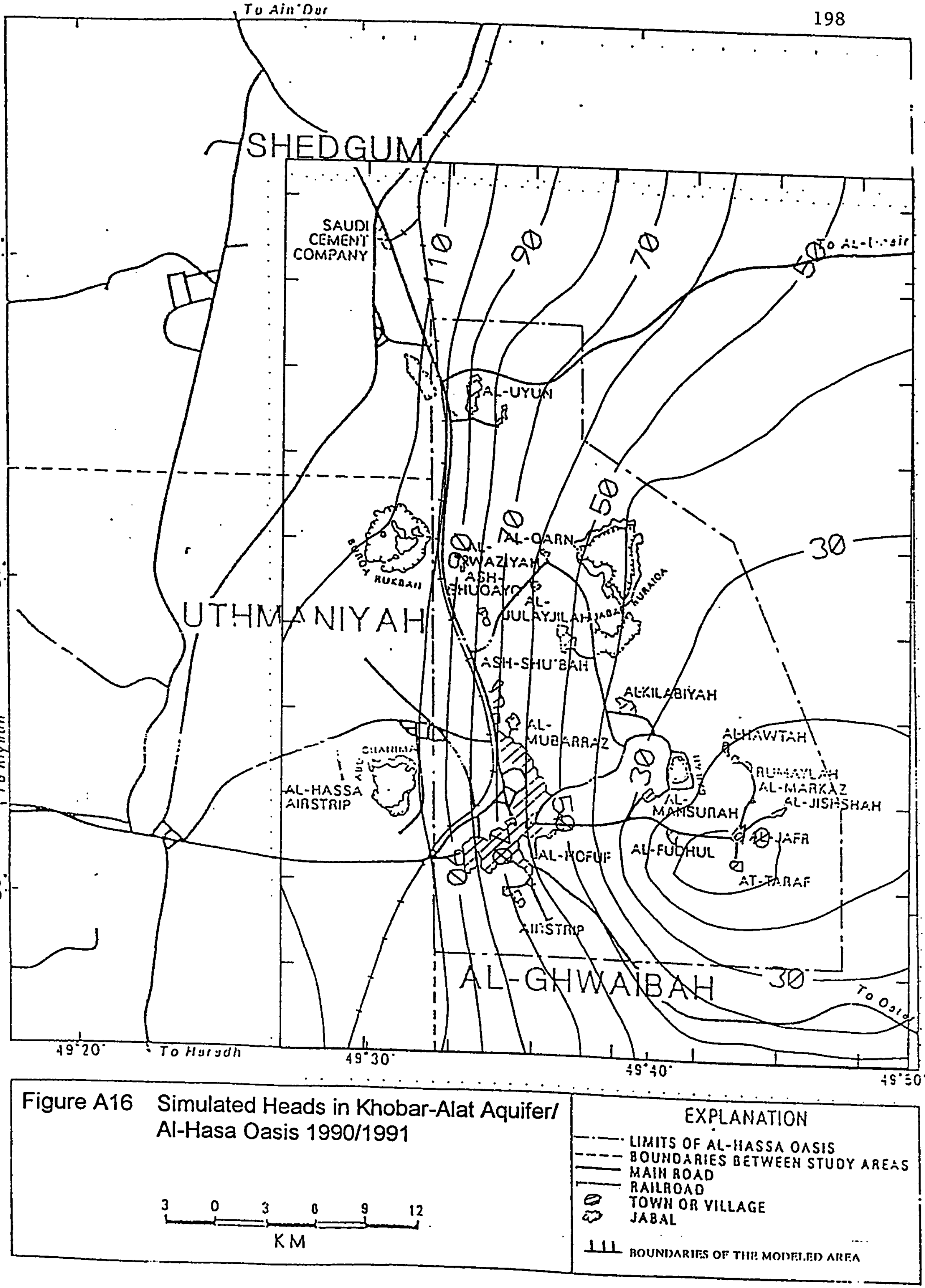


Figure A16 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1990/1991

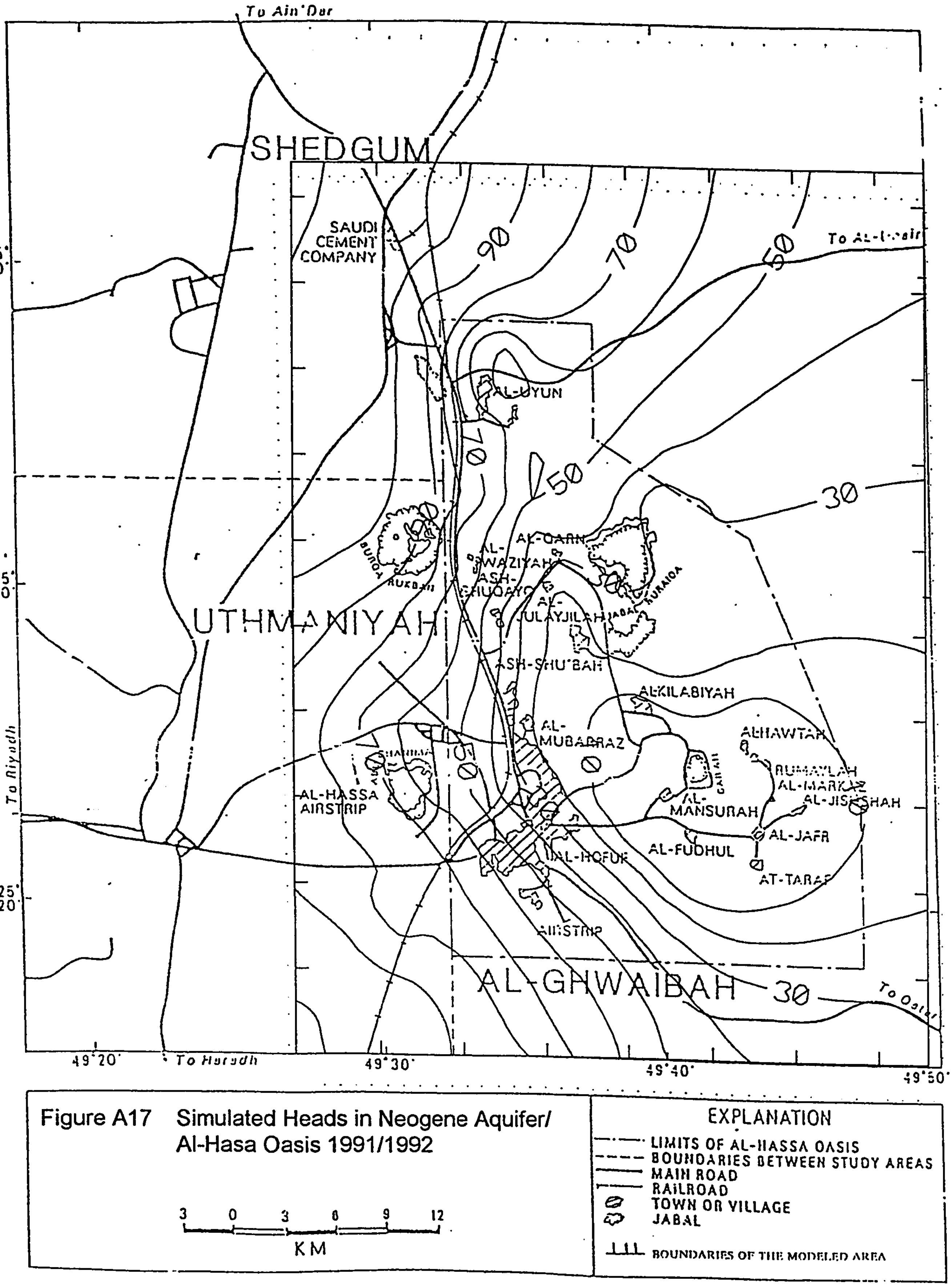


Figure A17 Simulated Heads in Neogene Aquifer/ Al-Hasa Oasis 1991/1992

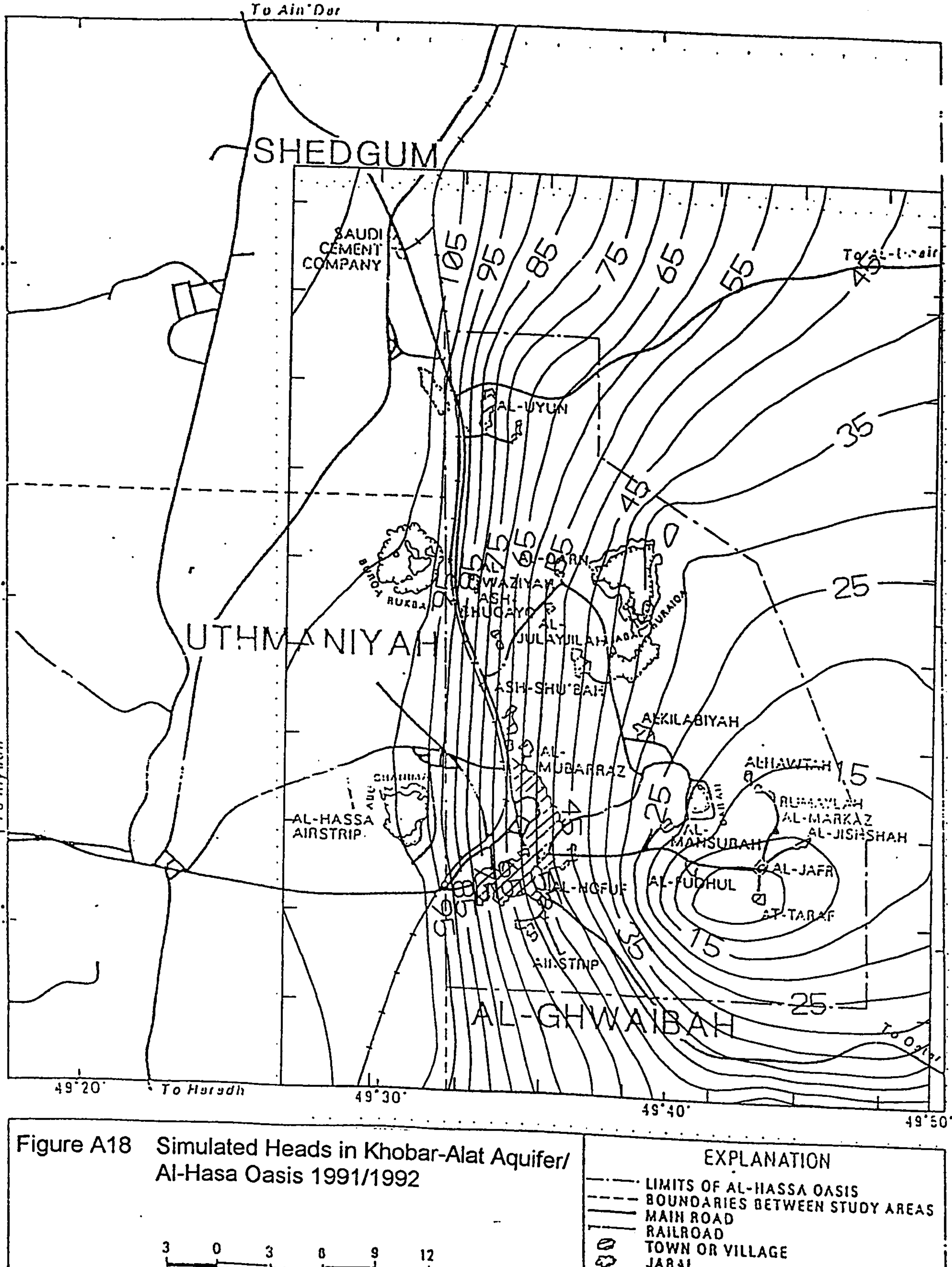


Figure A18 Simulated Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1991/1992

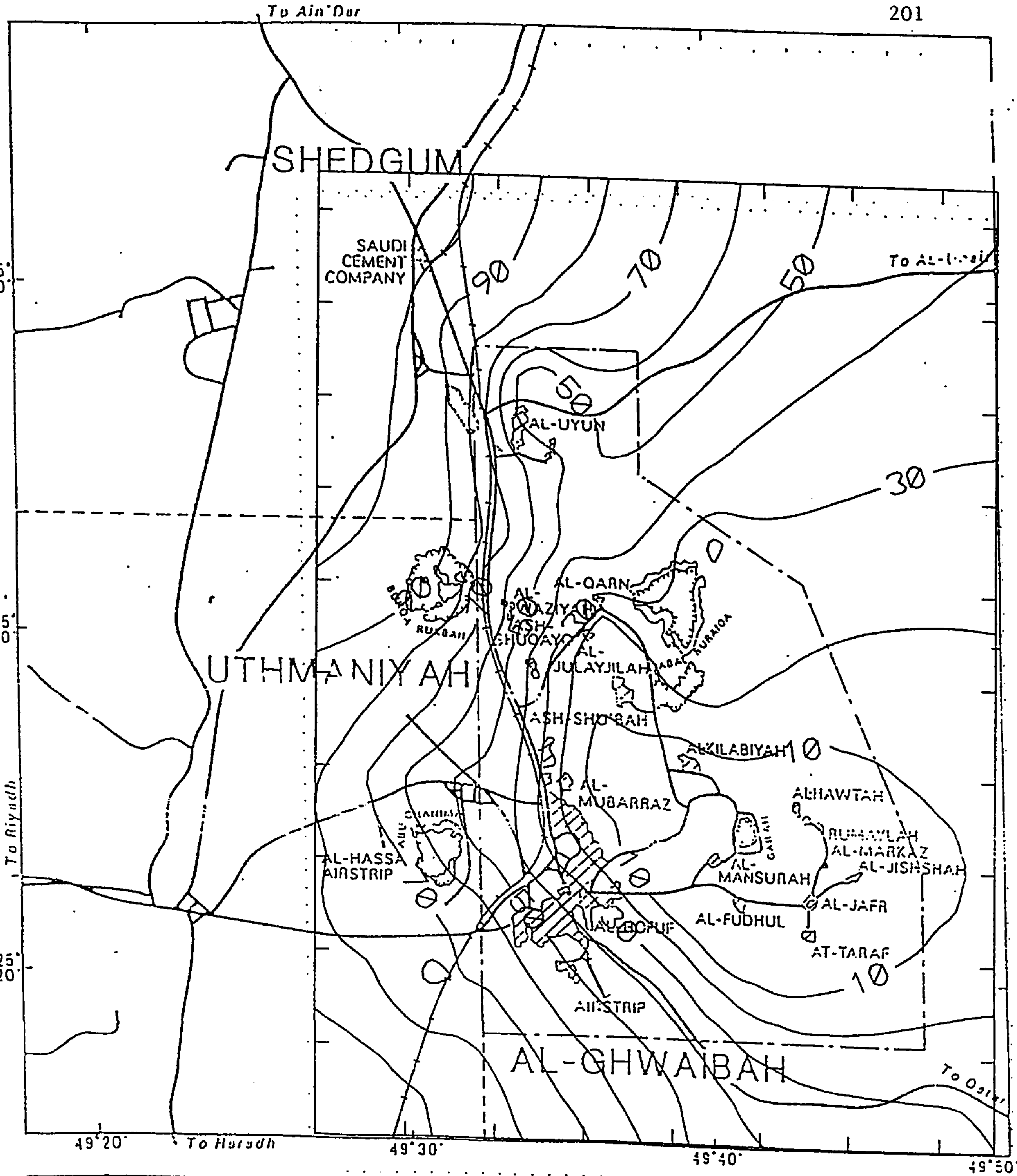


Figure A19 Predicted Heads in Neogene Aquifer/ Al-Hasa Oasis 1992/1993

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

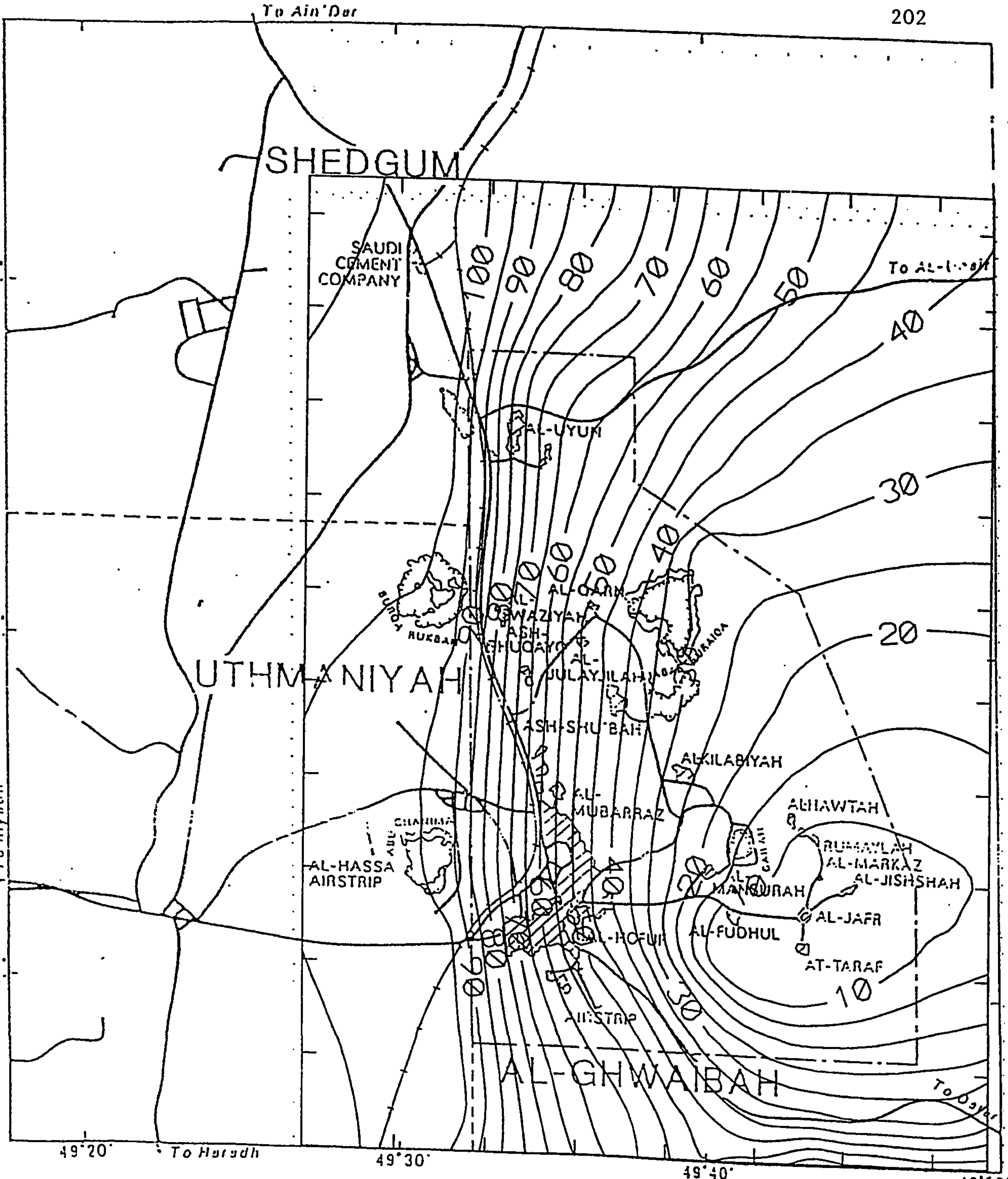


Figure A20 Predicted Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1992/1993

3 0 3 6 9 12

KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

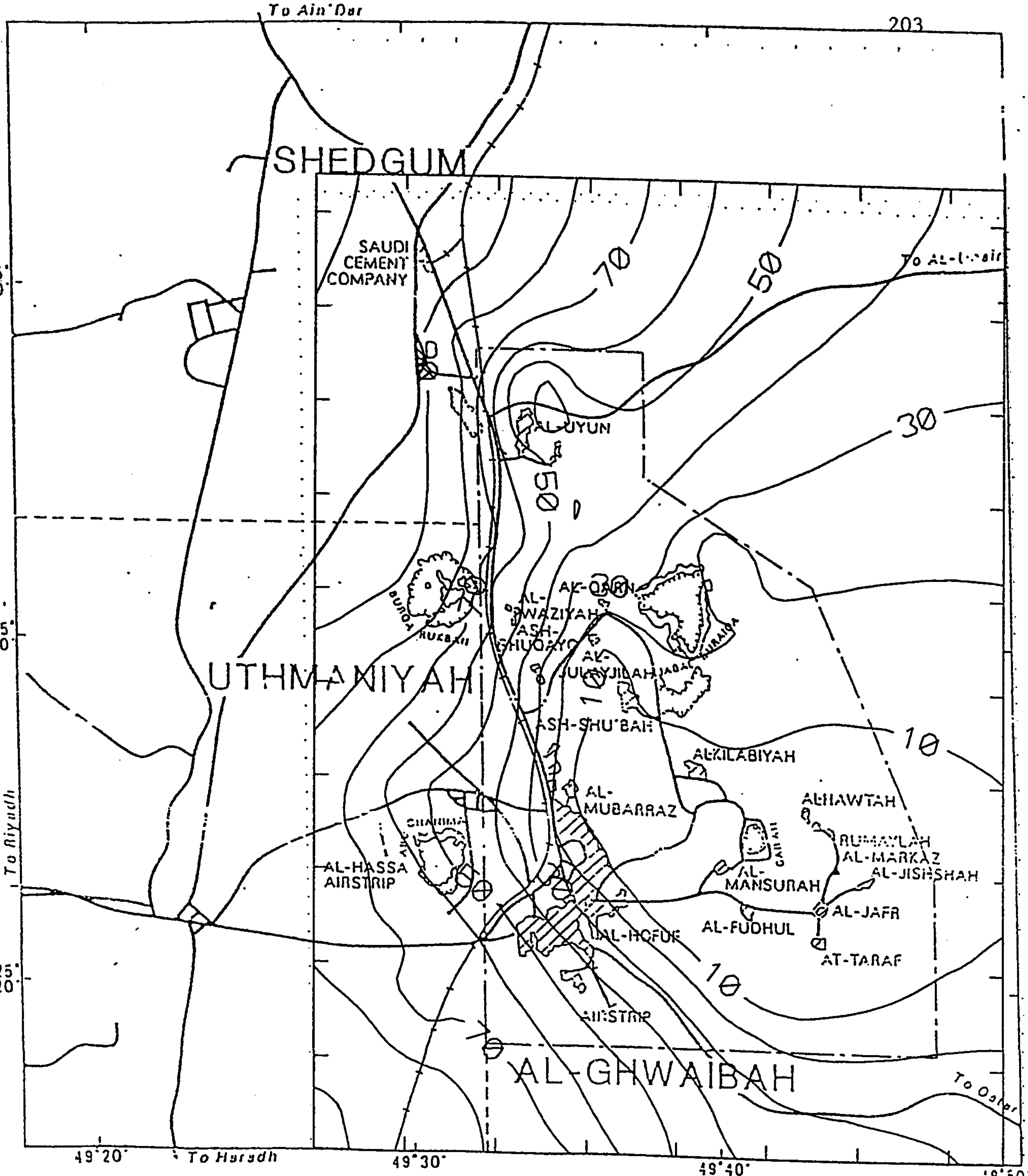


Figure A21 Predicted Heads in Neogene Aquifer/ Al-Hasa Oasis 1993/1994

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

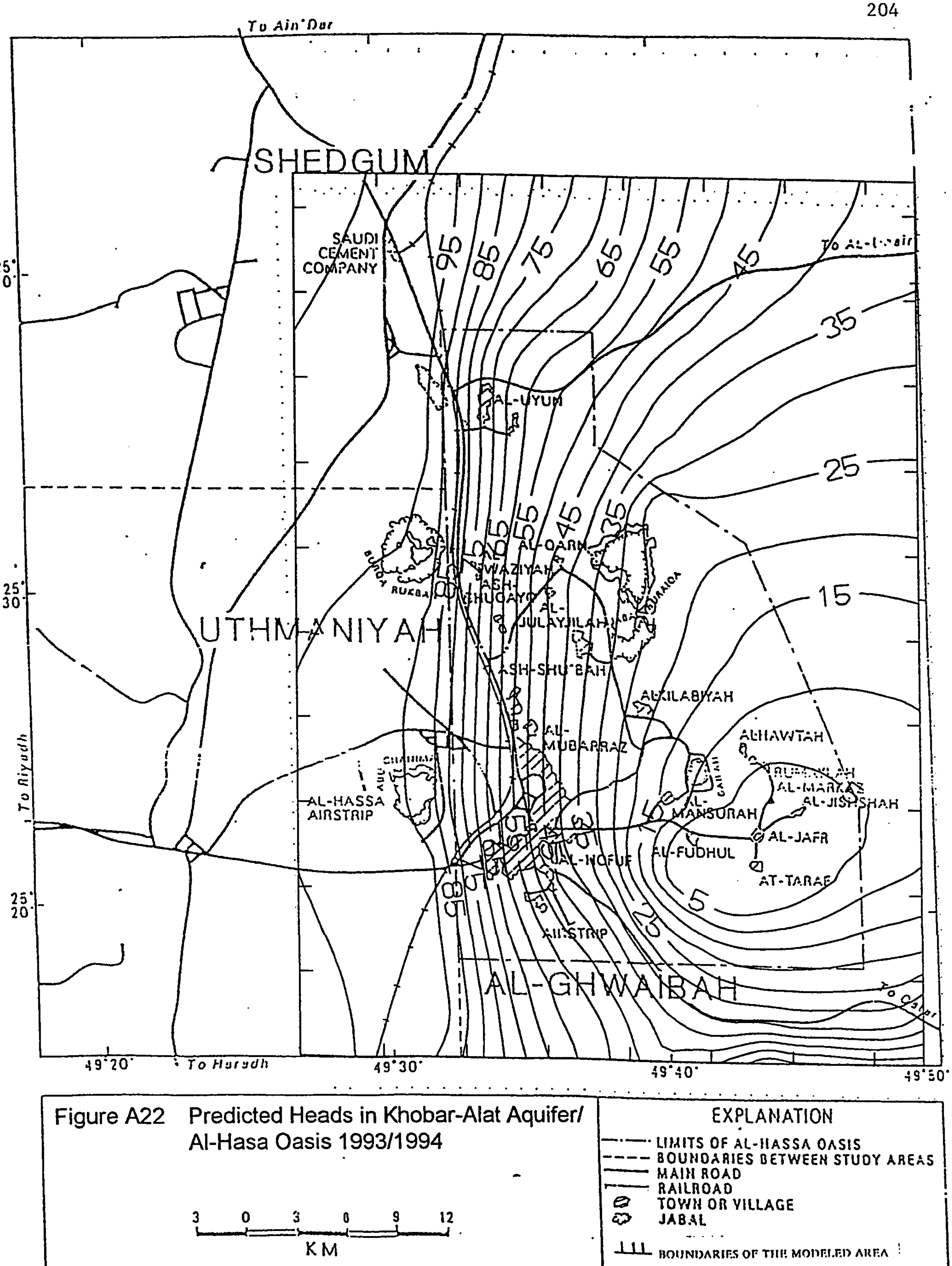


Figure A22 Predicted Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1993/1994

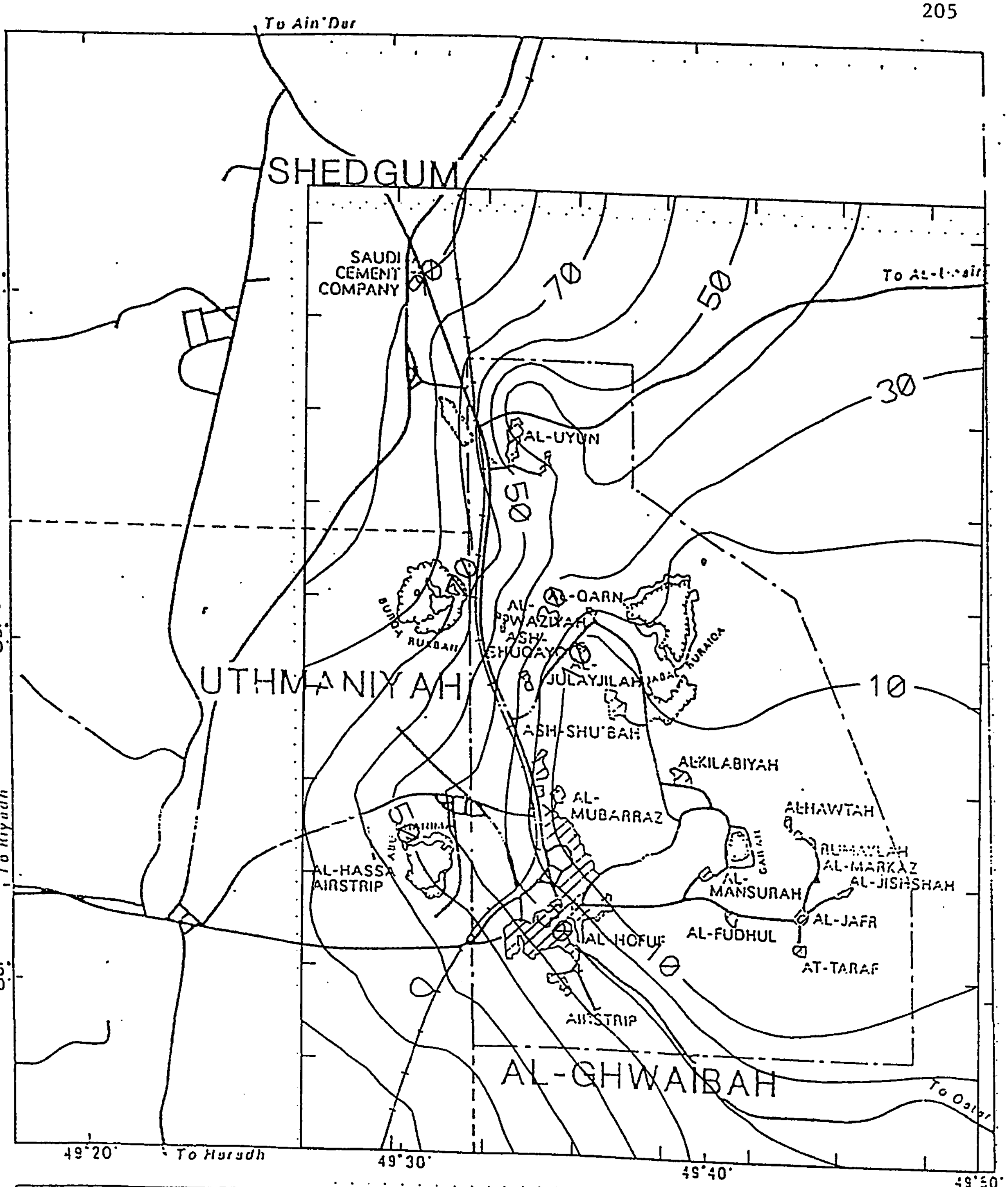


Figure A23 Predicted Heads in Neogene Aquifer/ Al-Hasa Oasis 1994/1995

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

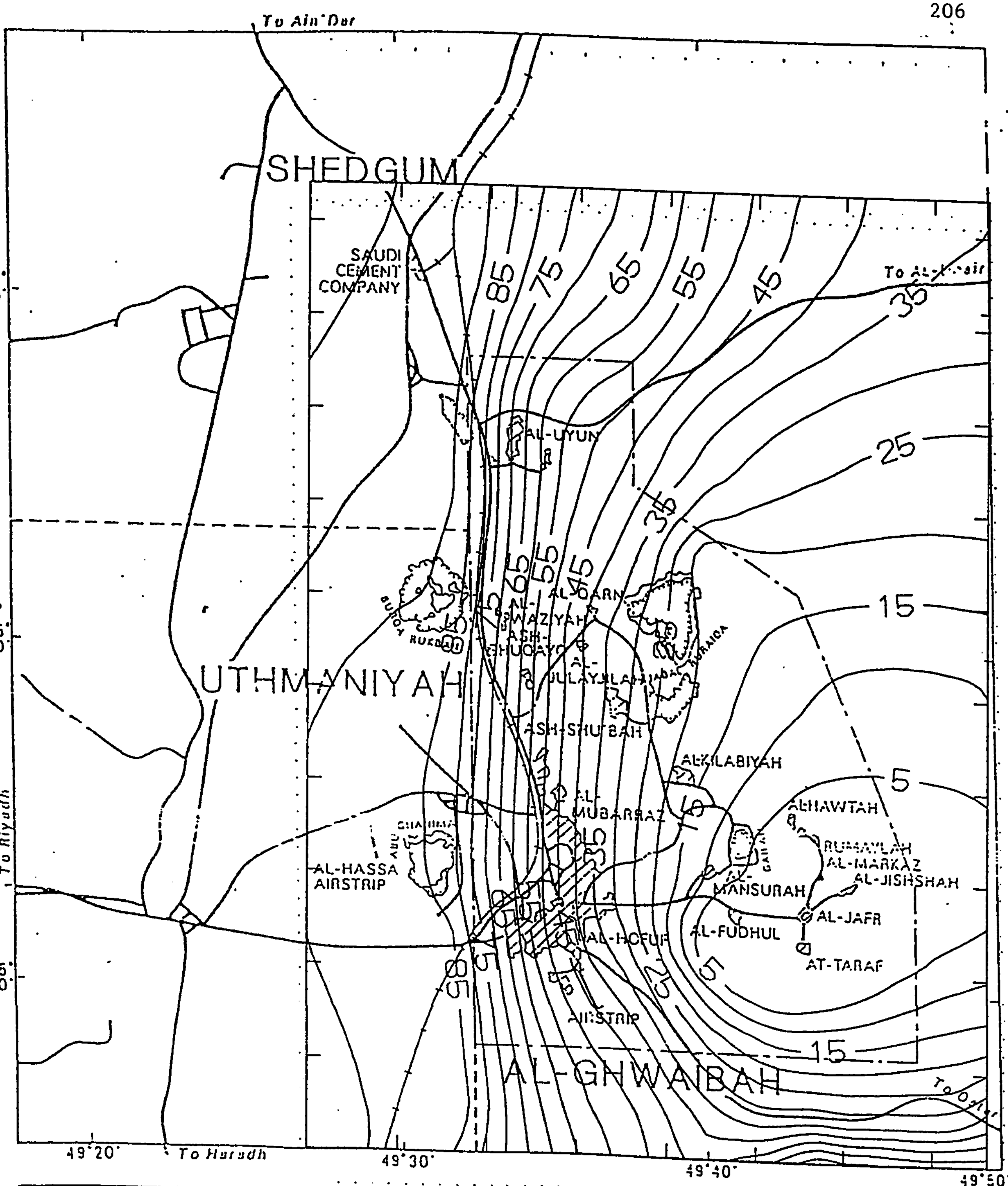


Figure A24 Predicted Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1994/1995

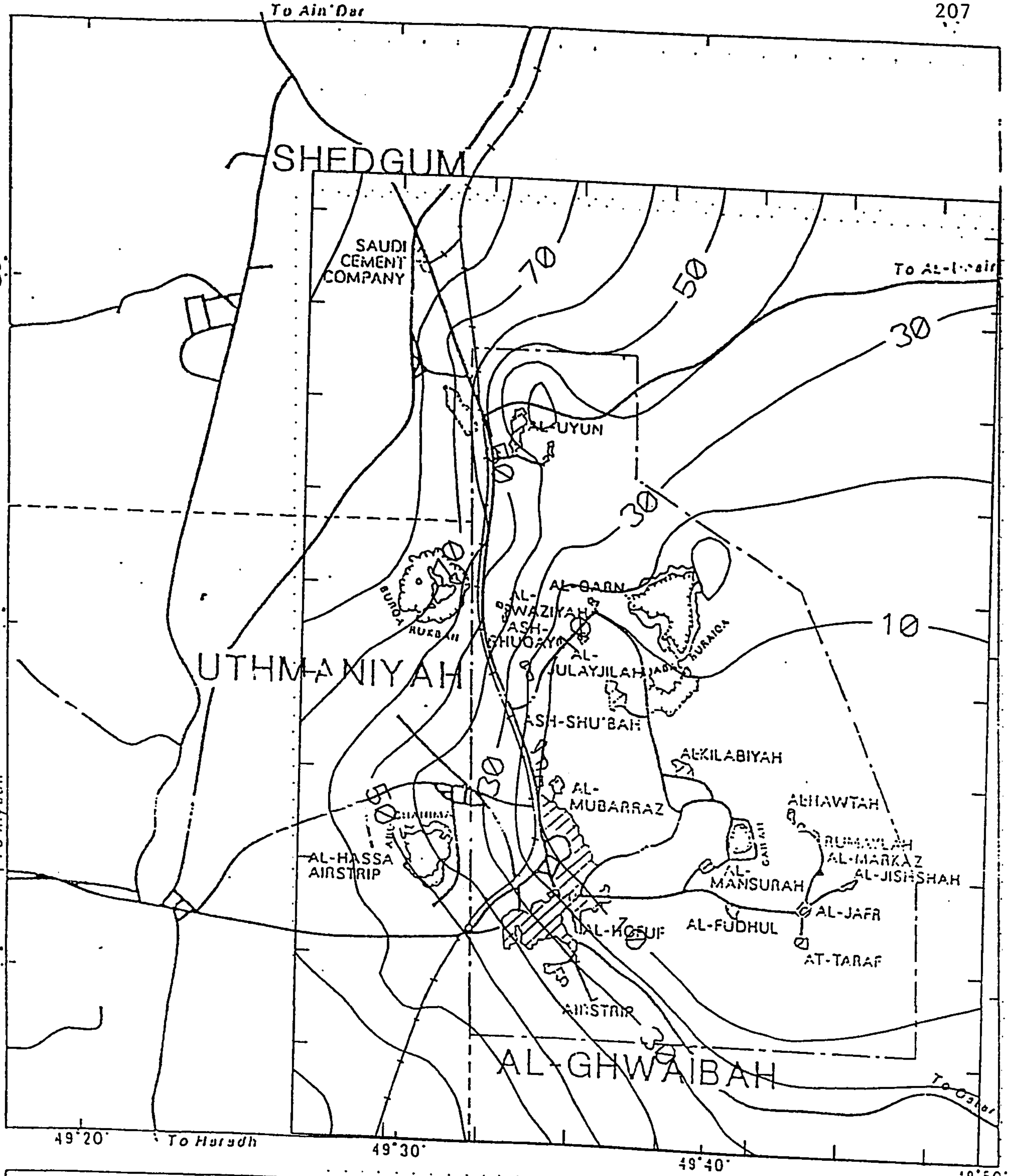


Figure A25 Predicted Heads in Neogene Aquifer/ Al-Hasa Oasis 1995/1996

3 0 3 6 9 12

KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

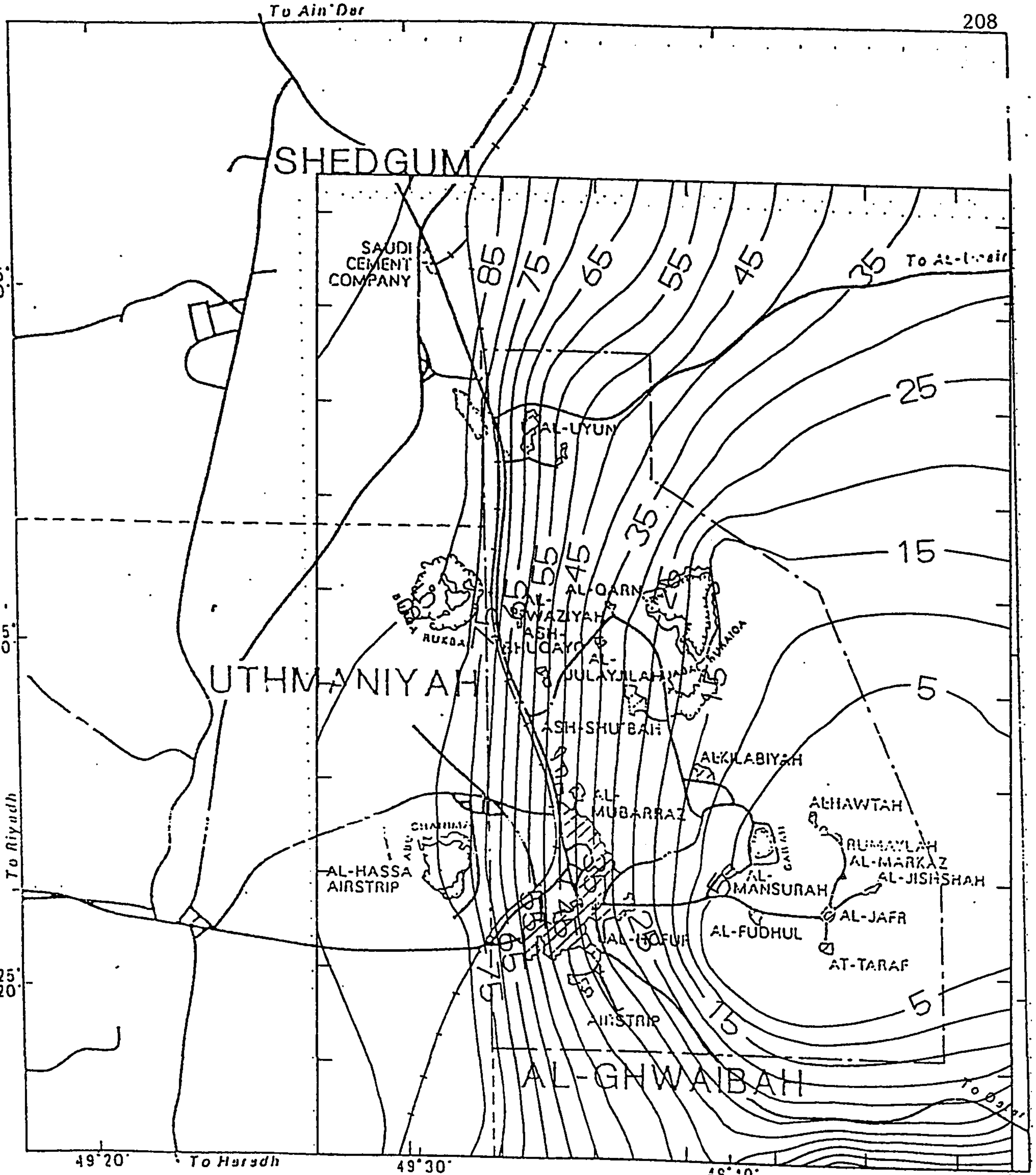
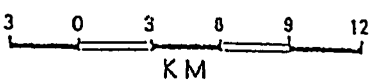


Figure A26 Predicted Heads in Khobar-Alat Aquifer/ Al-Hasa Oasis 1995/1996



EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

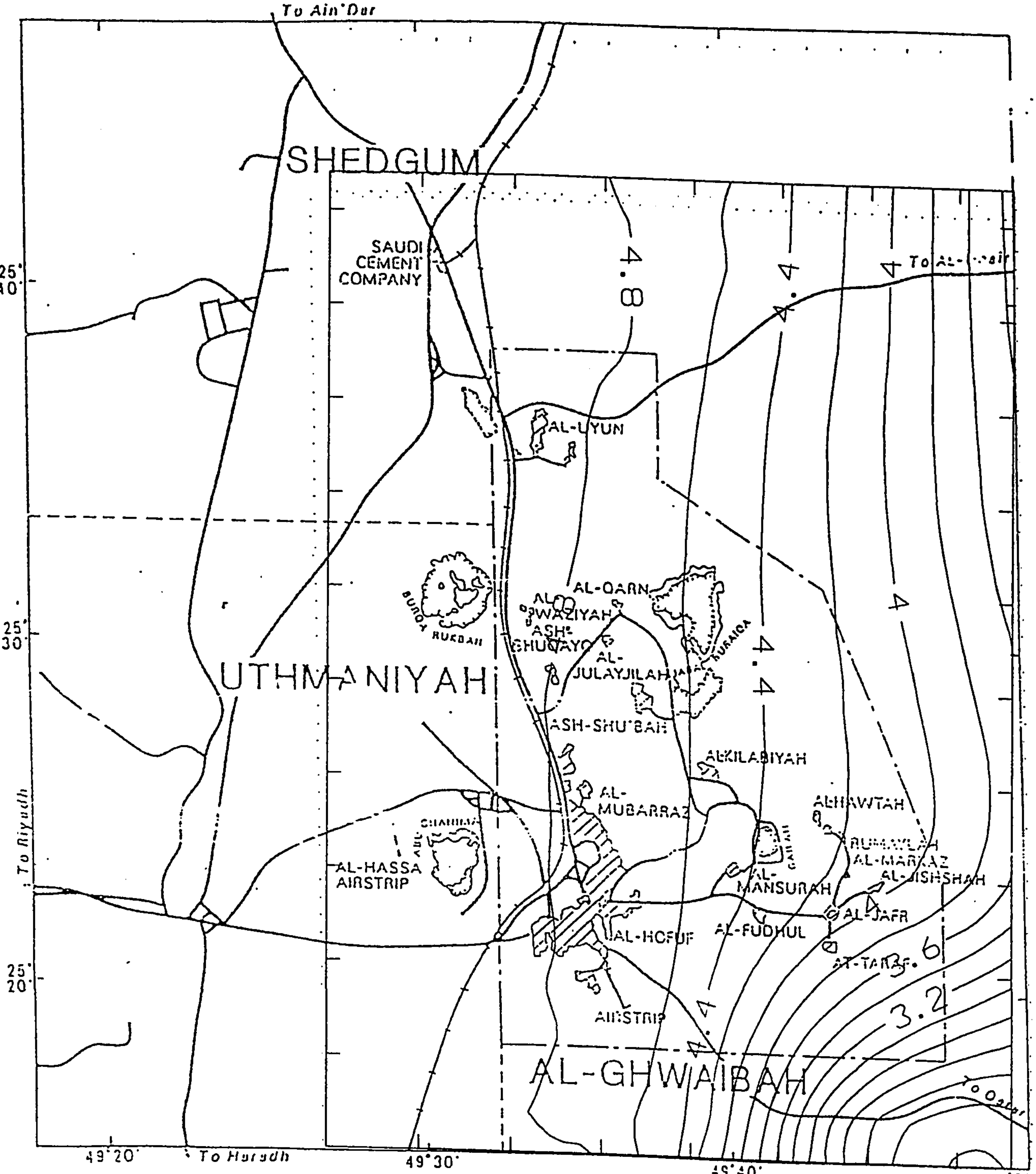
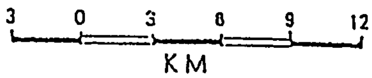


Figure A27 Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1983/1984



EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

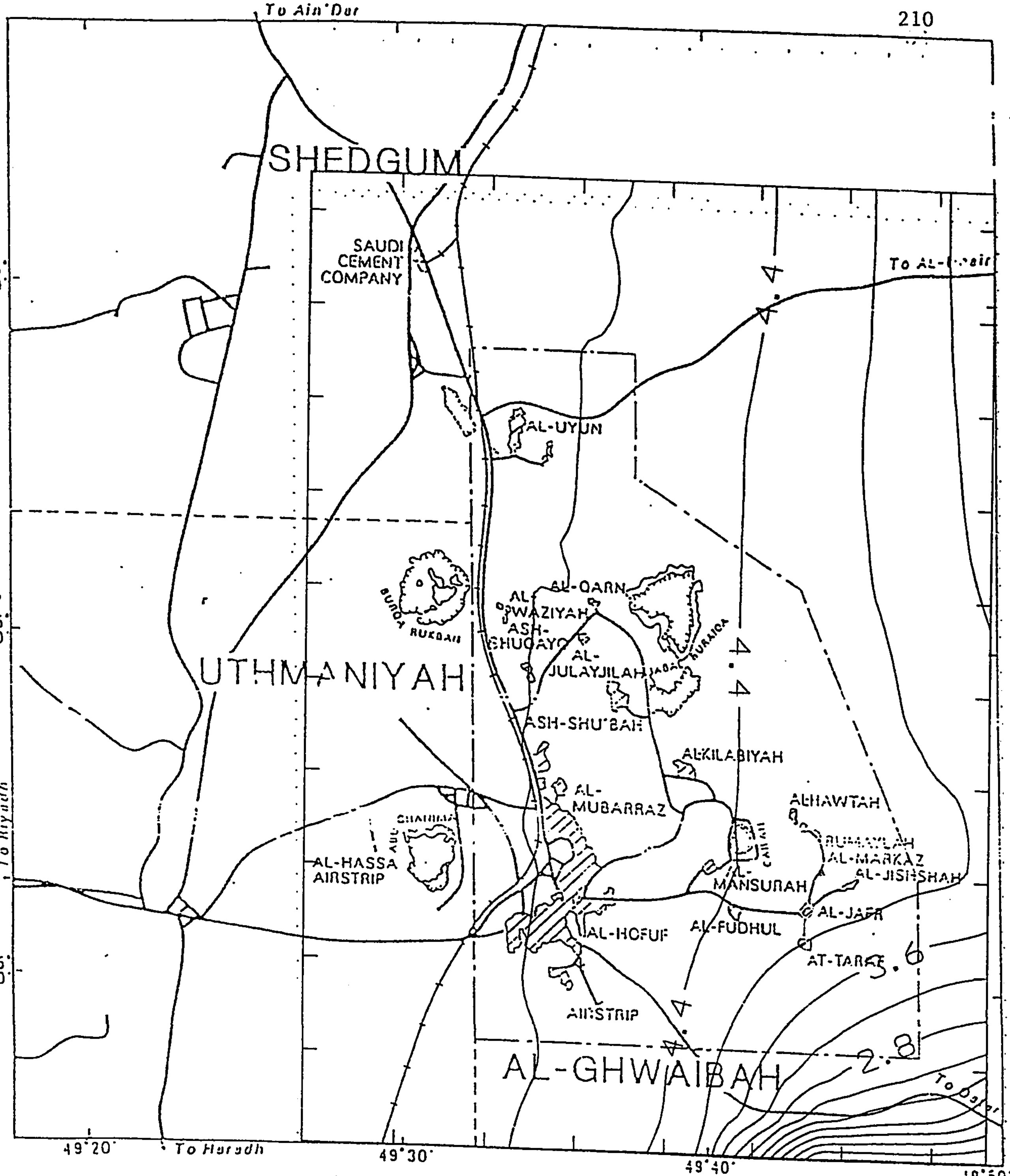


Figure A28 Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1983/1984

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

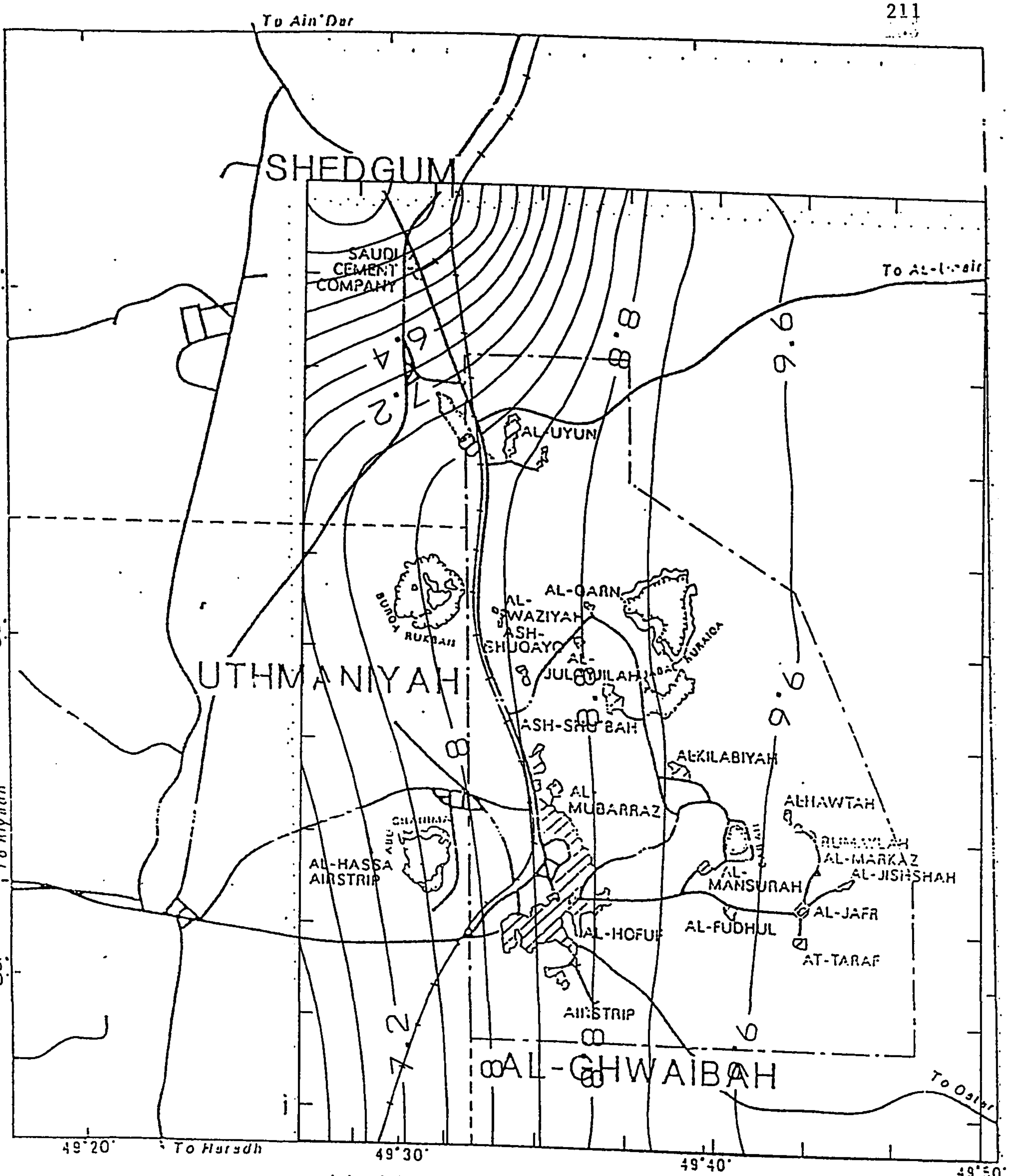


Figure A29 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1984/1985

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

3 0 3 6 9 12

KM

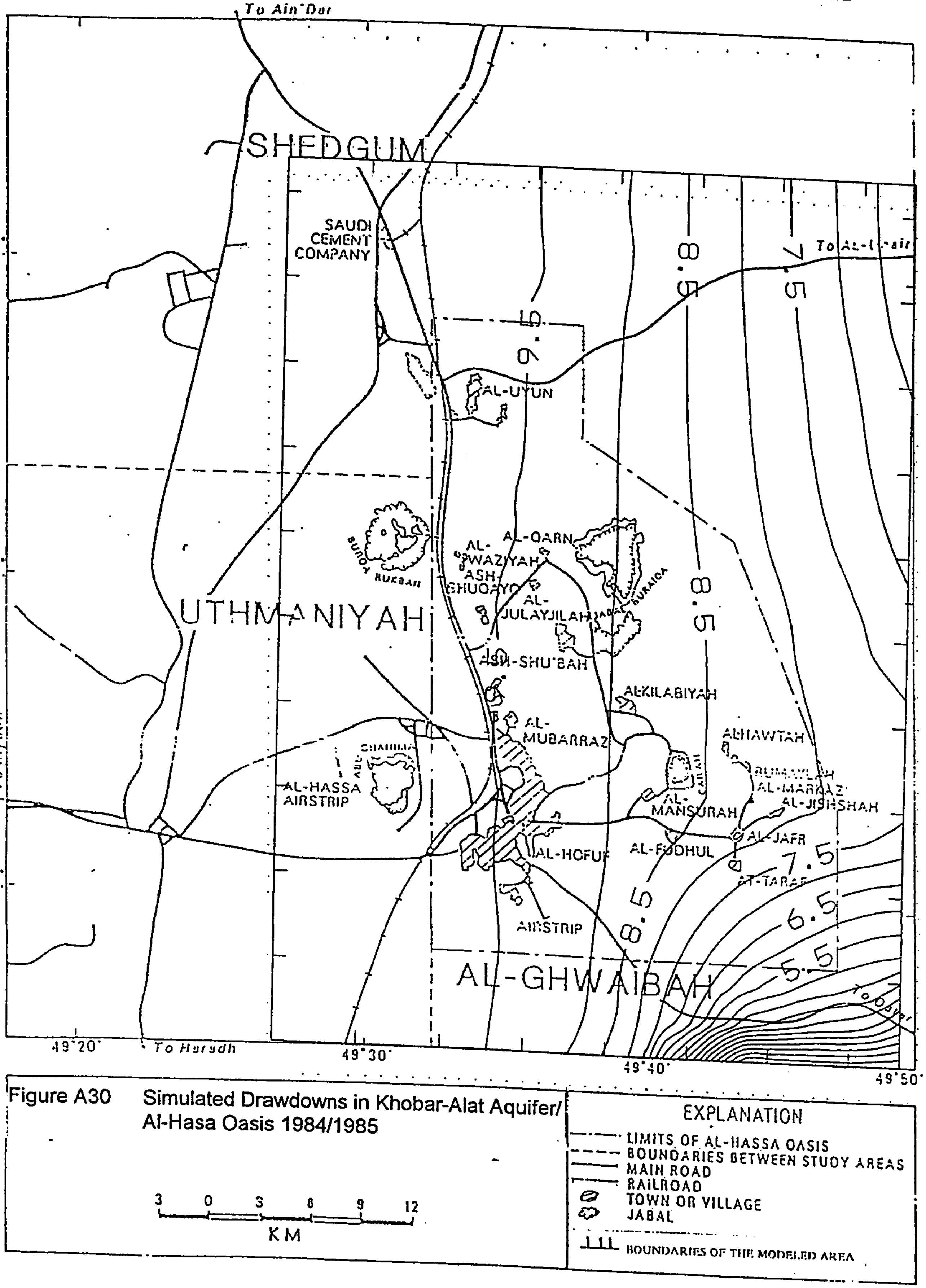


Figure A30 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1984/1985

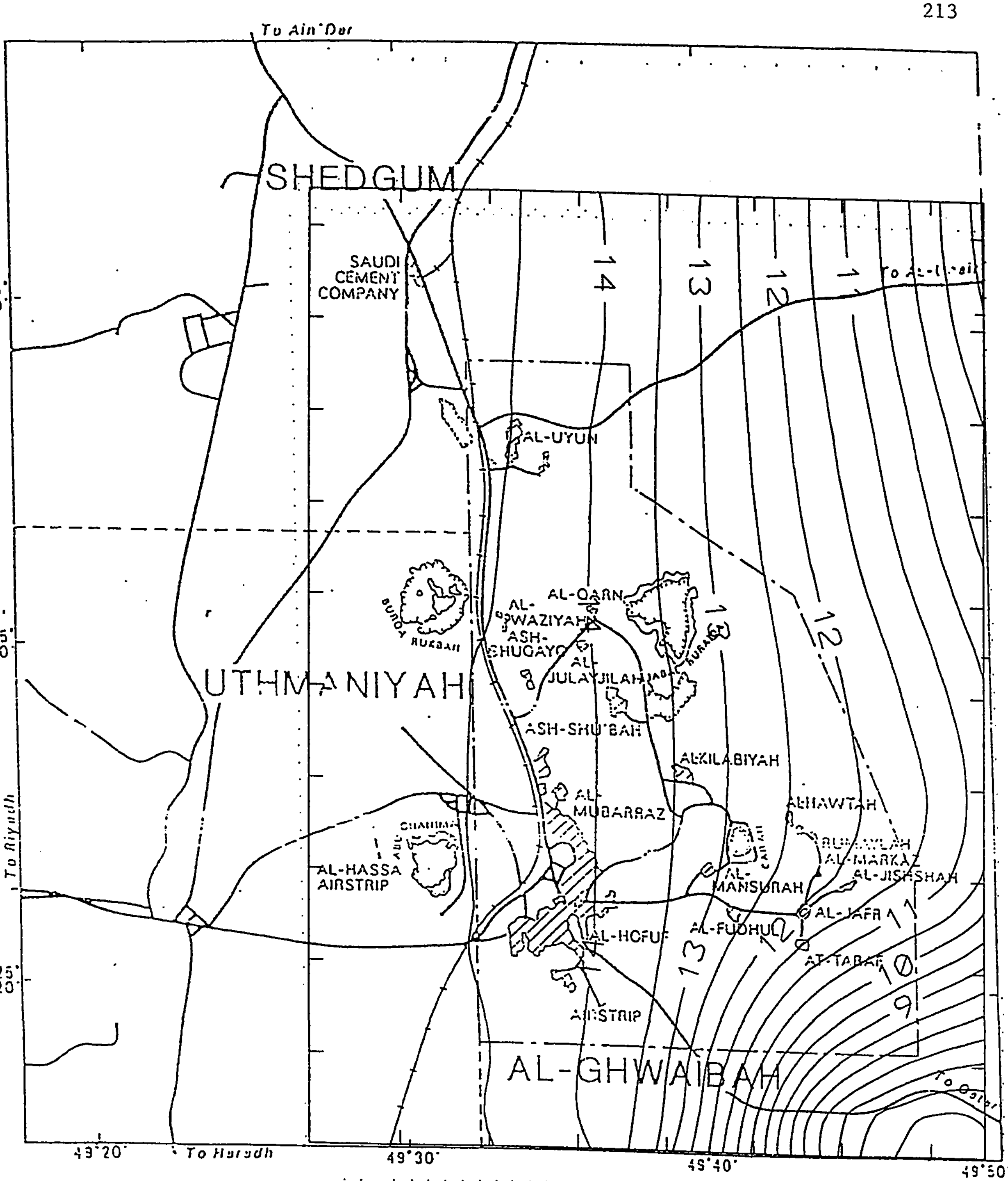


Figure A31 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1985/1986

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

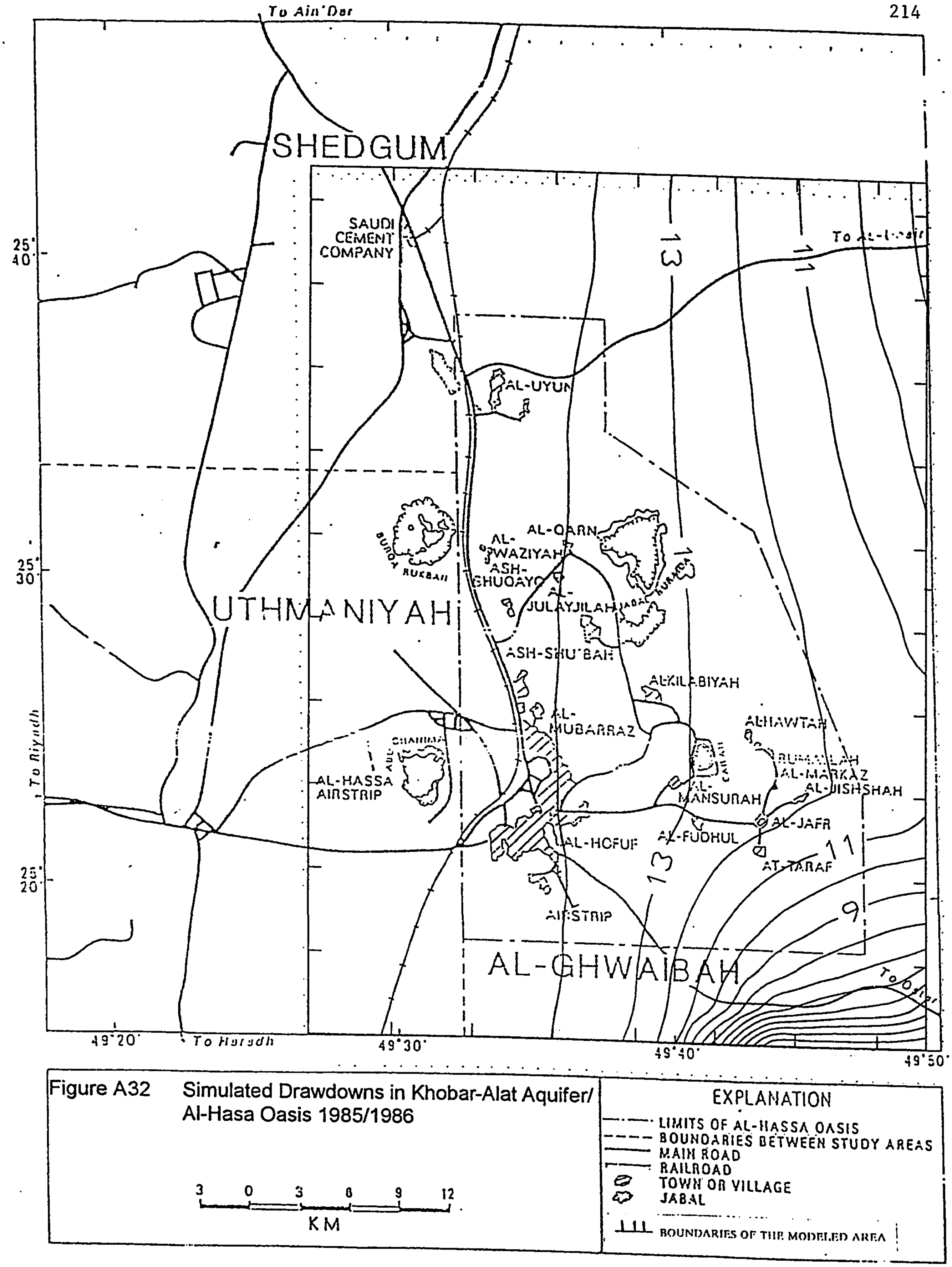


Figure A32 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1985/1986

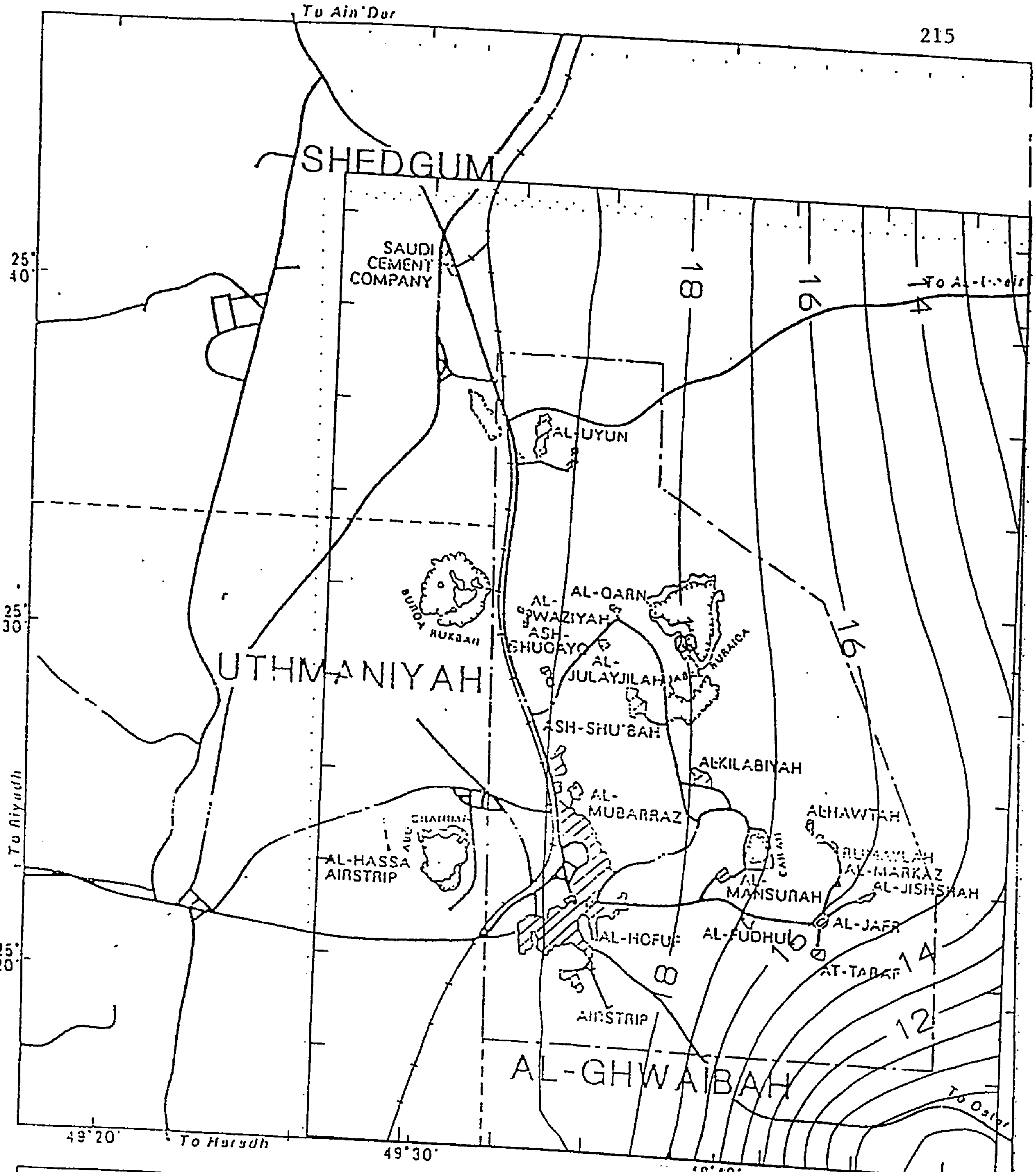


Figure A33 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1986/1987

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

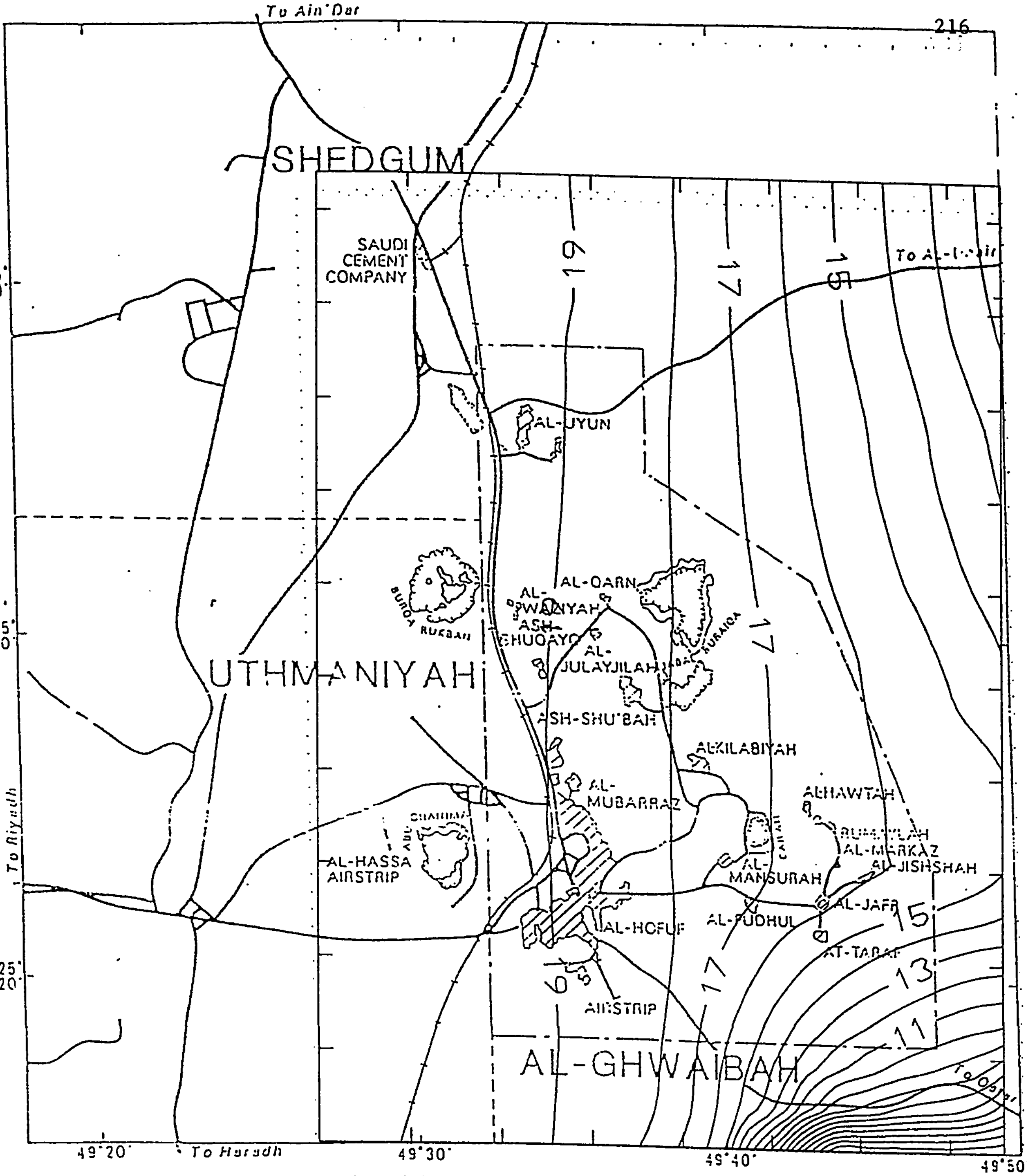
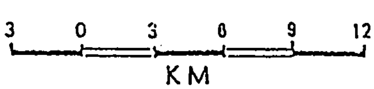


Figure A34 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1986/1987



EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

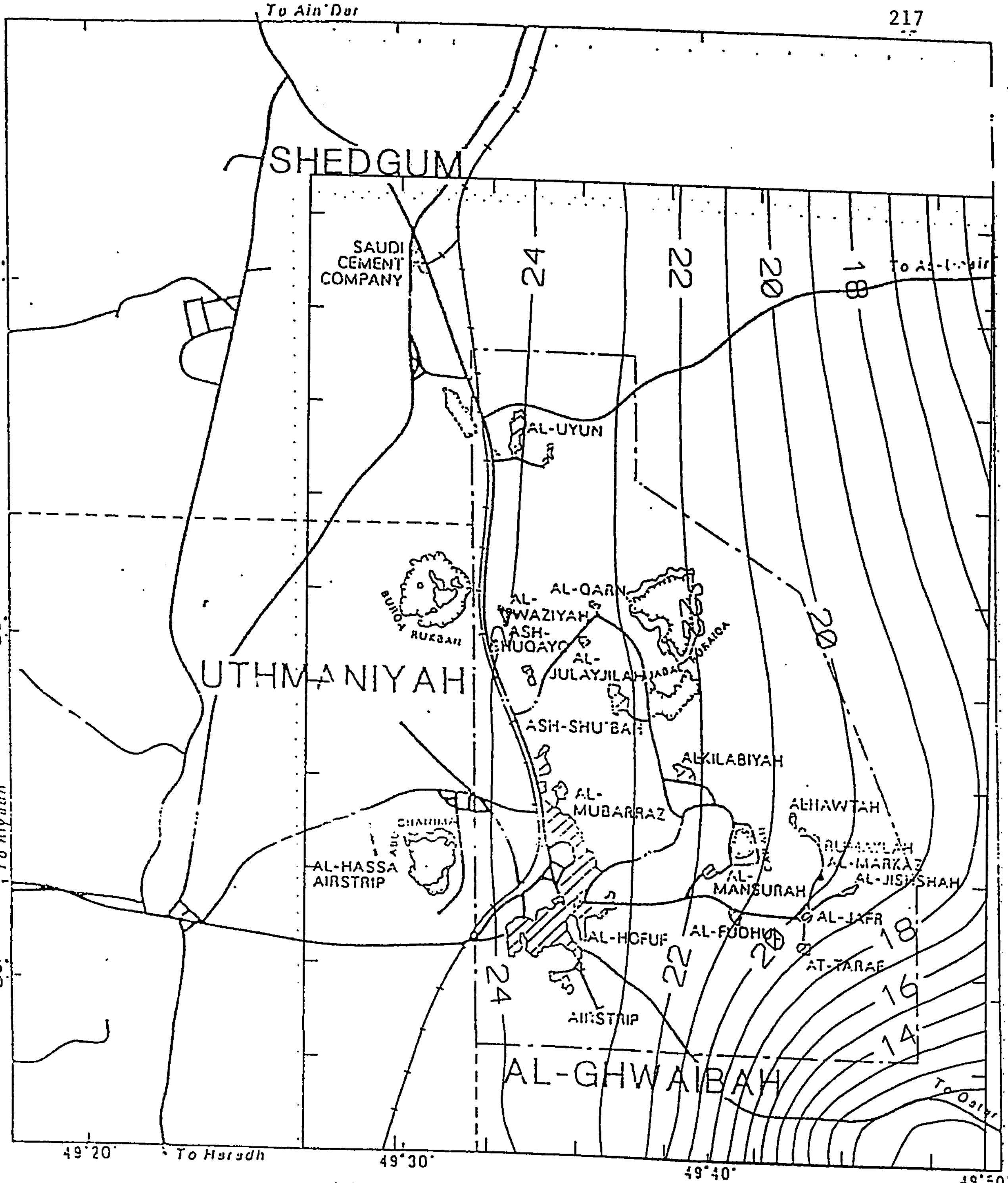


Figure A35 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1987/1988

3 0 3 6 9 12
KM

EXPLANATION
- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

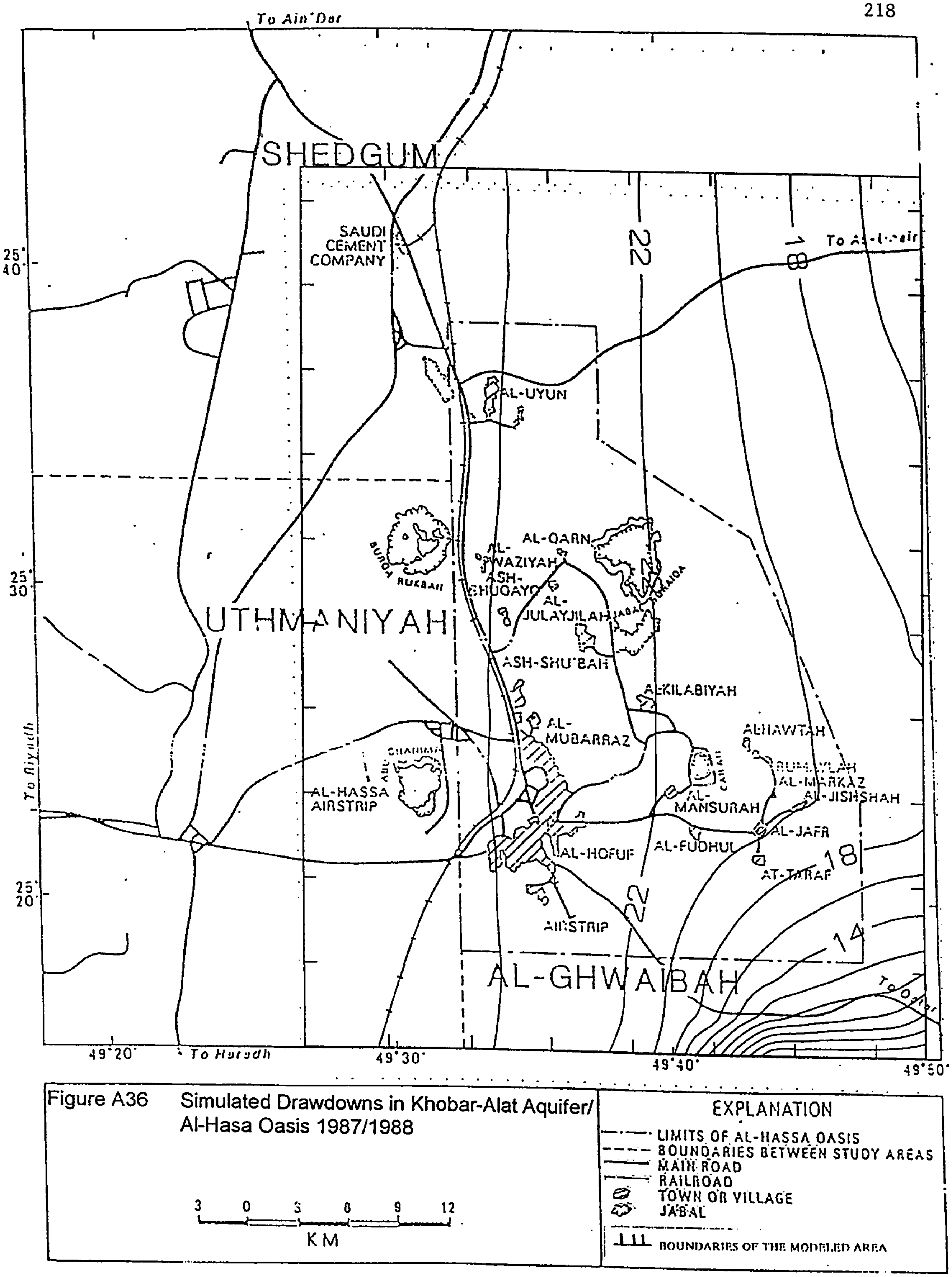


Figure A36 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1987/1988

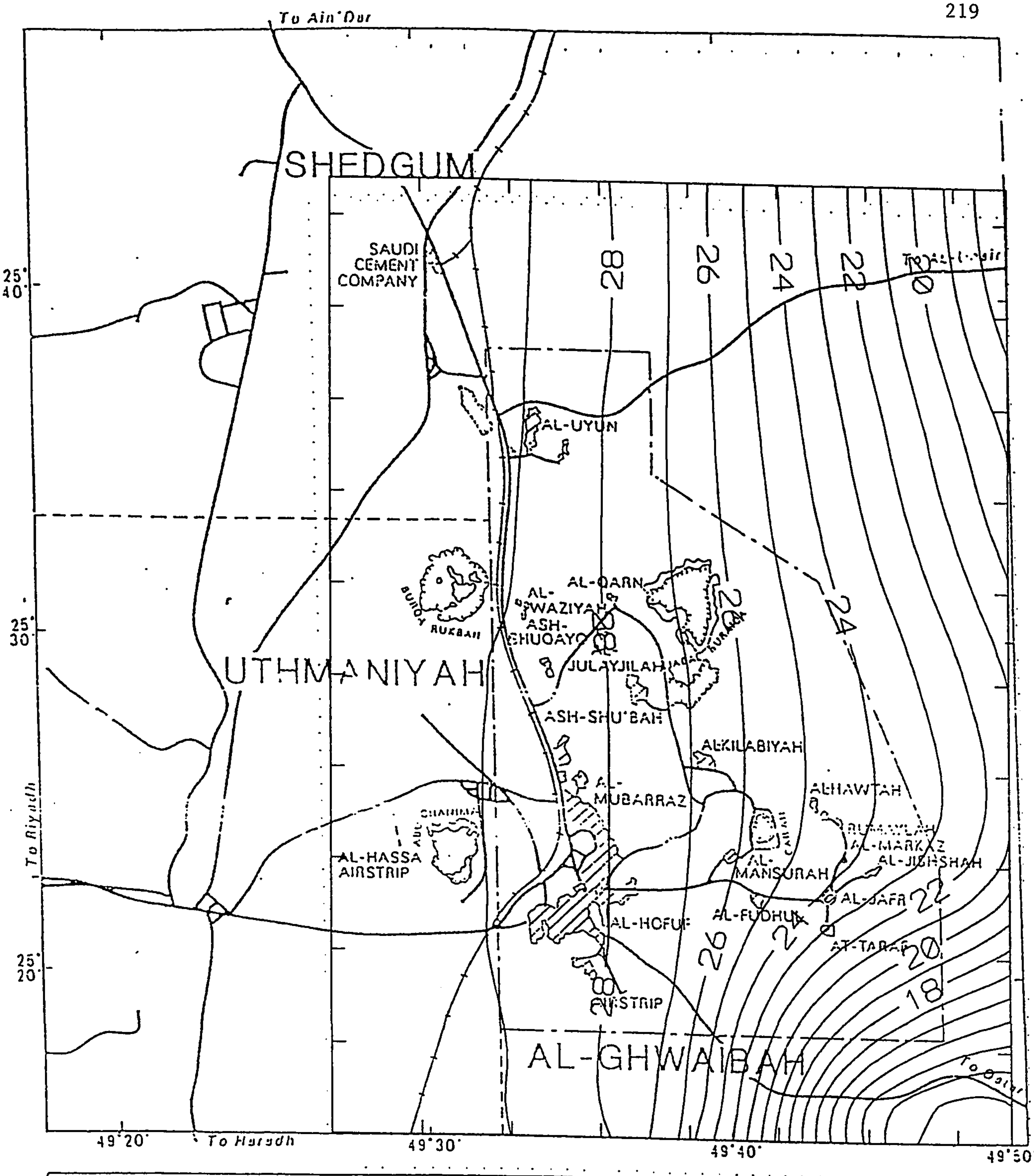


Figure A37 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1988/1989

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

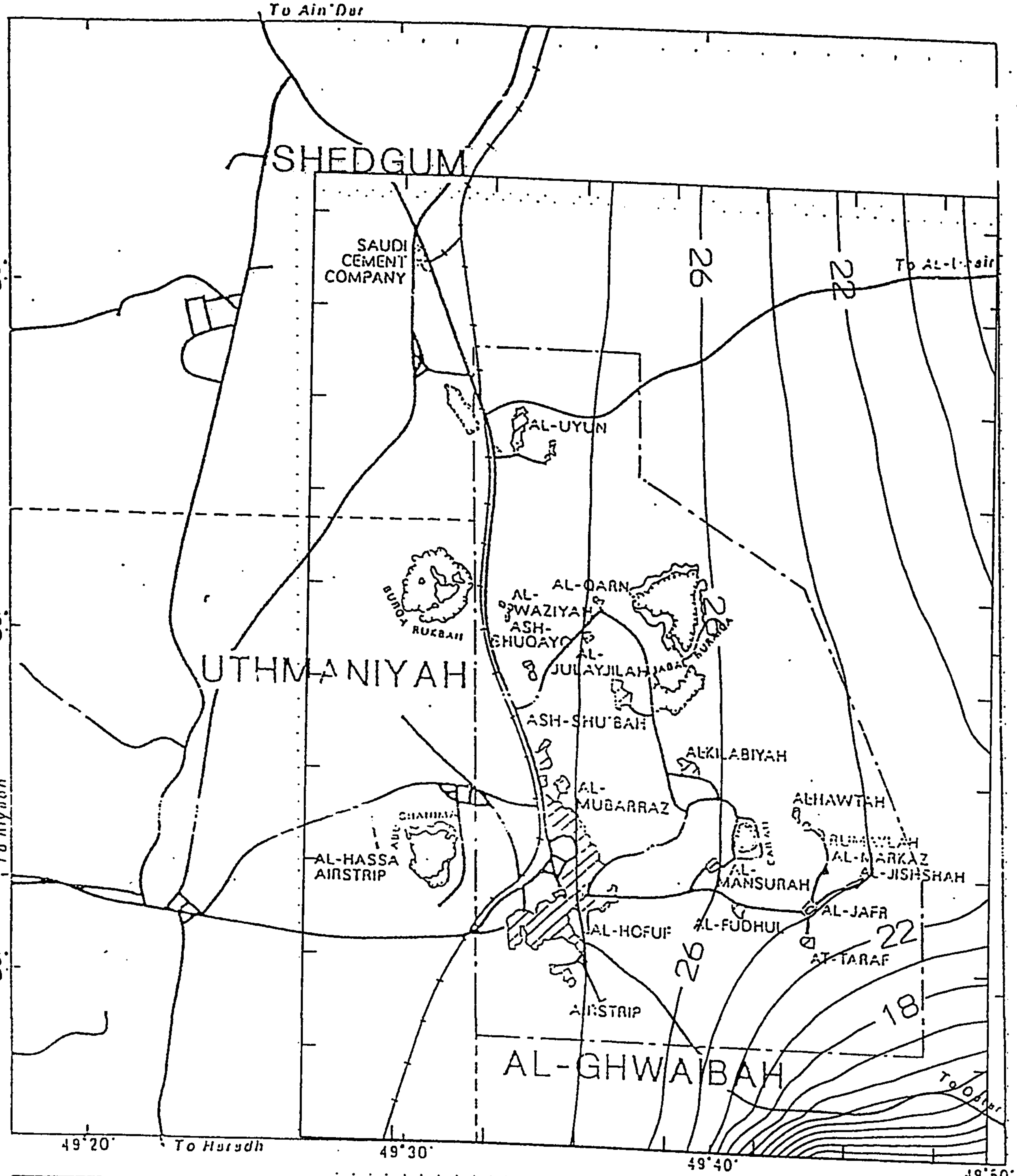


Figure A38 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1988/1989

3 0 3 6 9 12
KM

EXPLANATION
LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

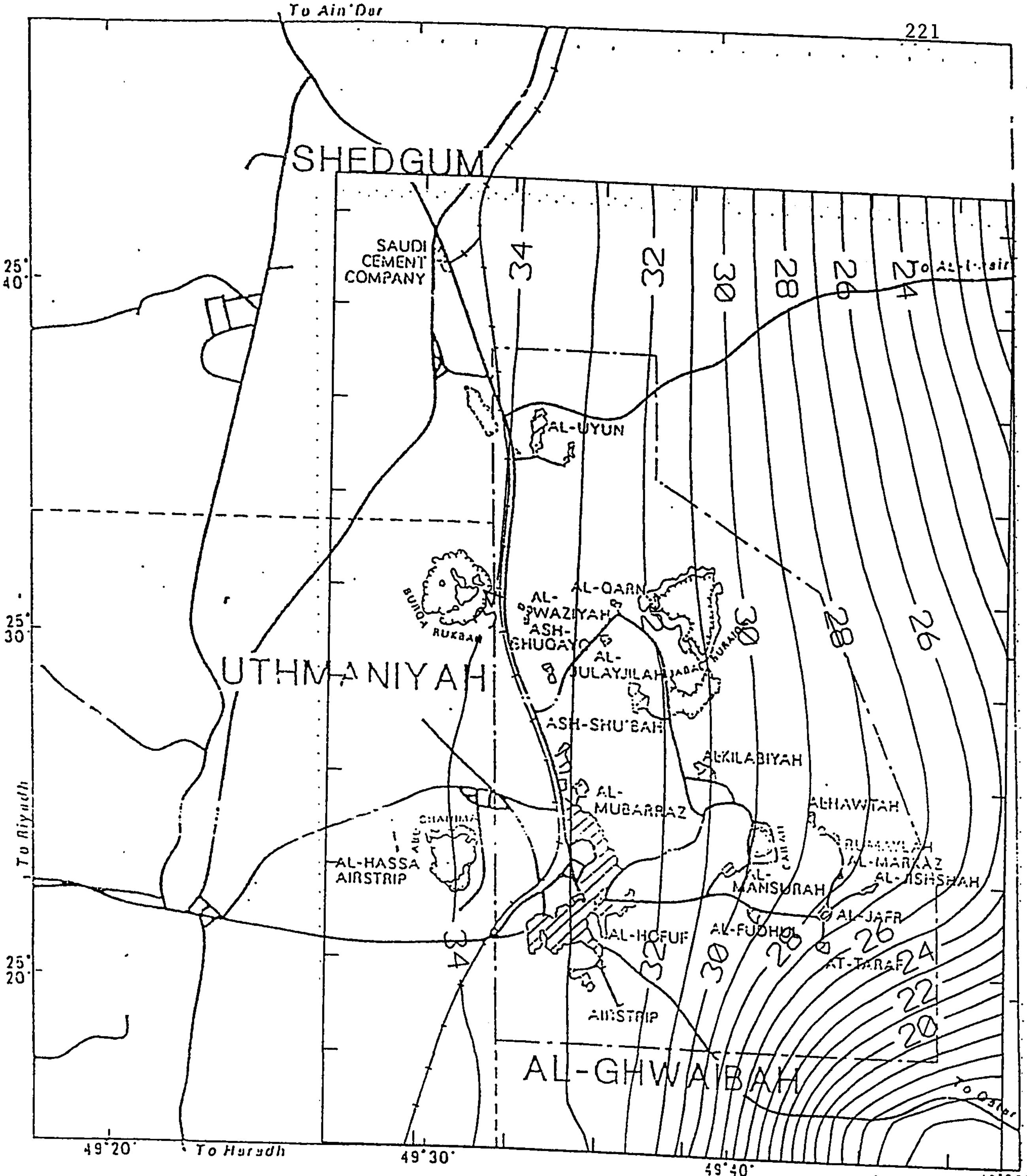


Figure A39 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1989/1990

3 0 3 6 9 12
KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

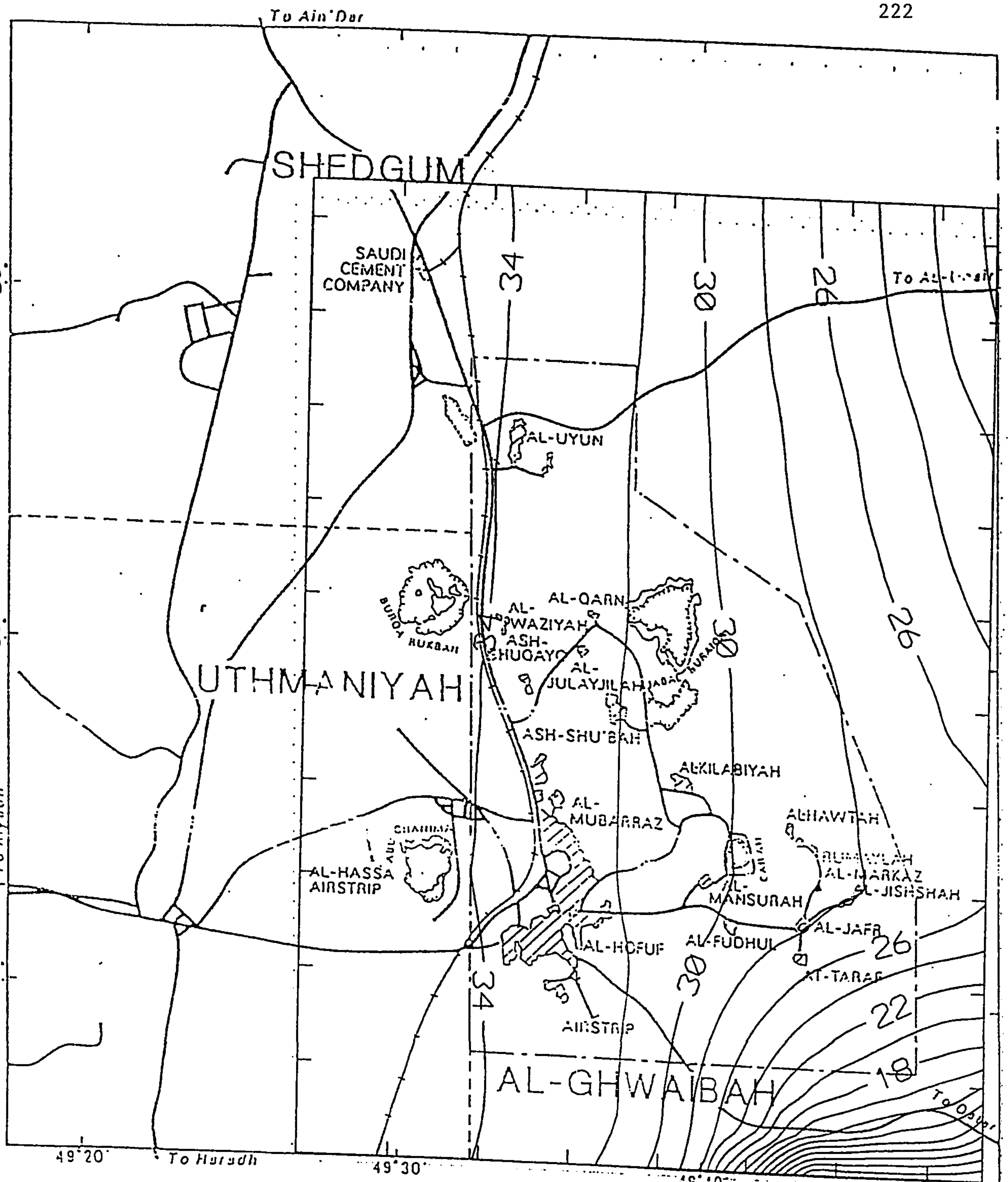


Figure A40 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1989/1990

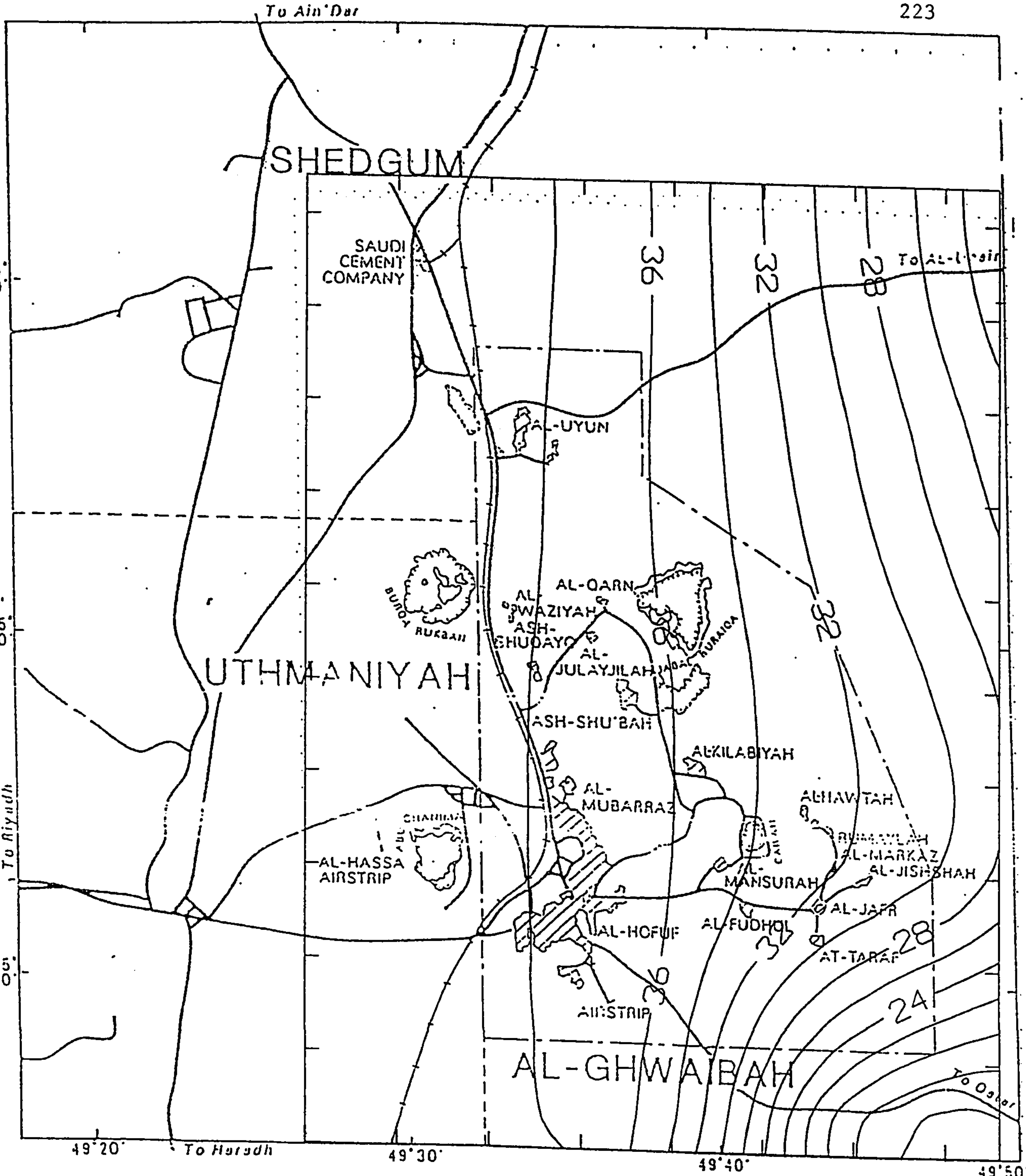


Figure A41 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1990/1991

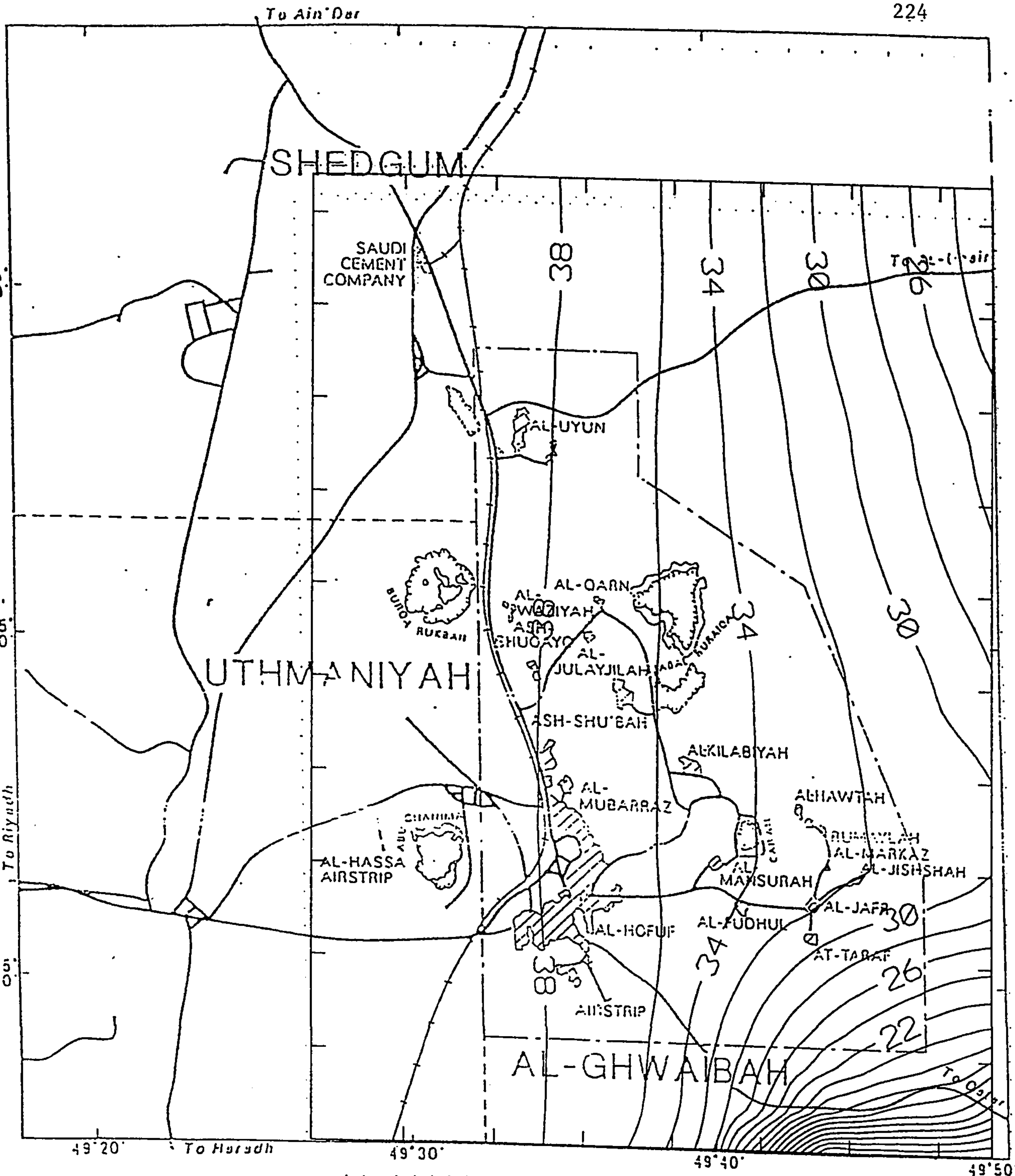


Figure A42 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1990/1991

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

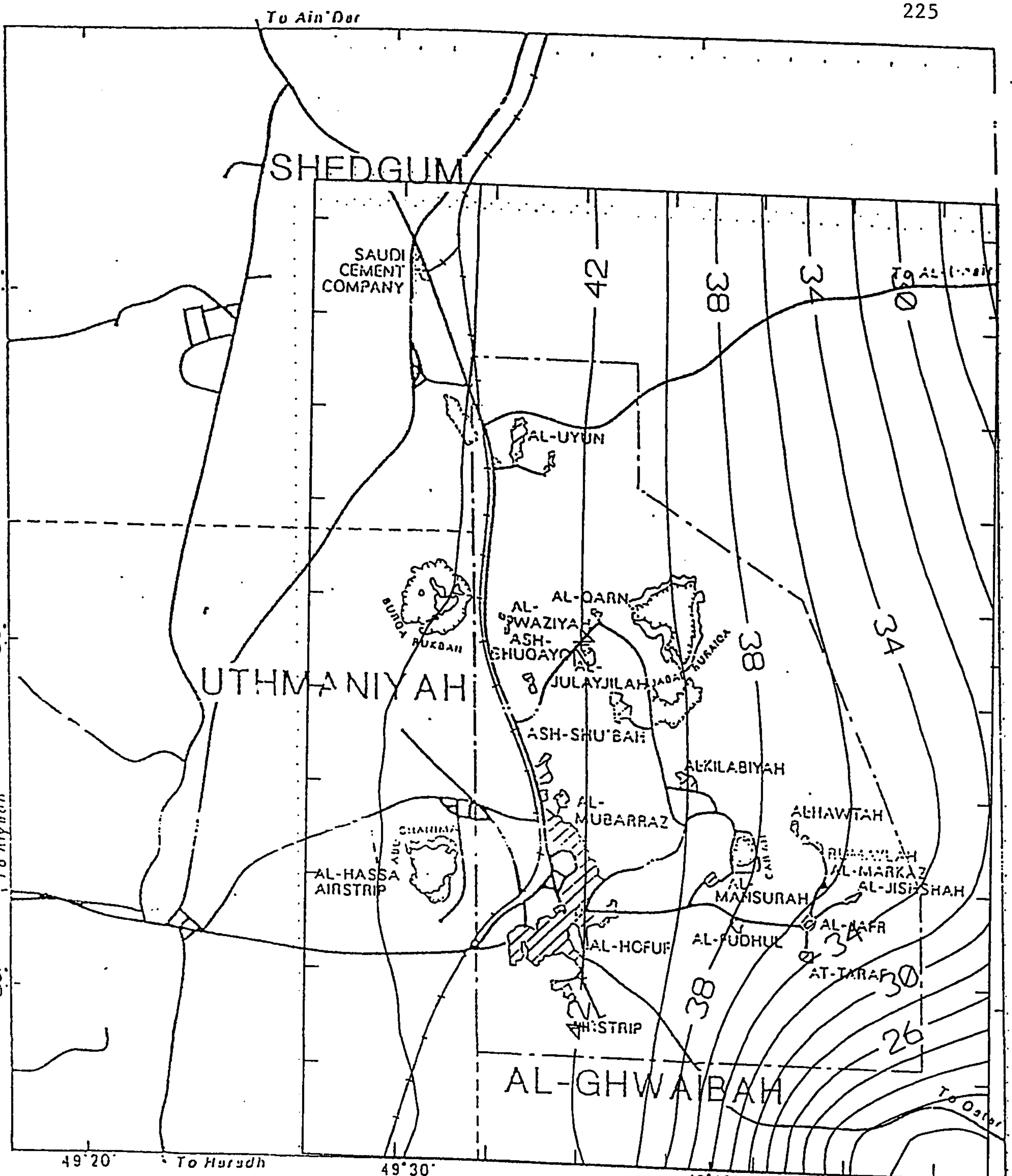
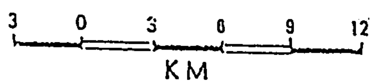
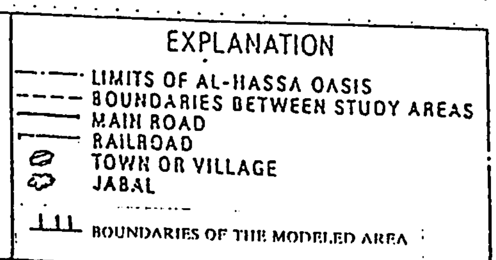


Figure A43 Simulated Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1991/1992





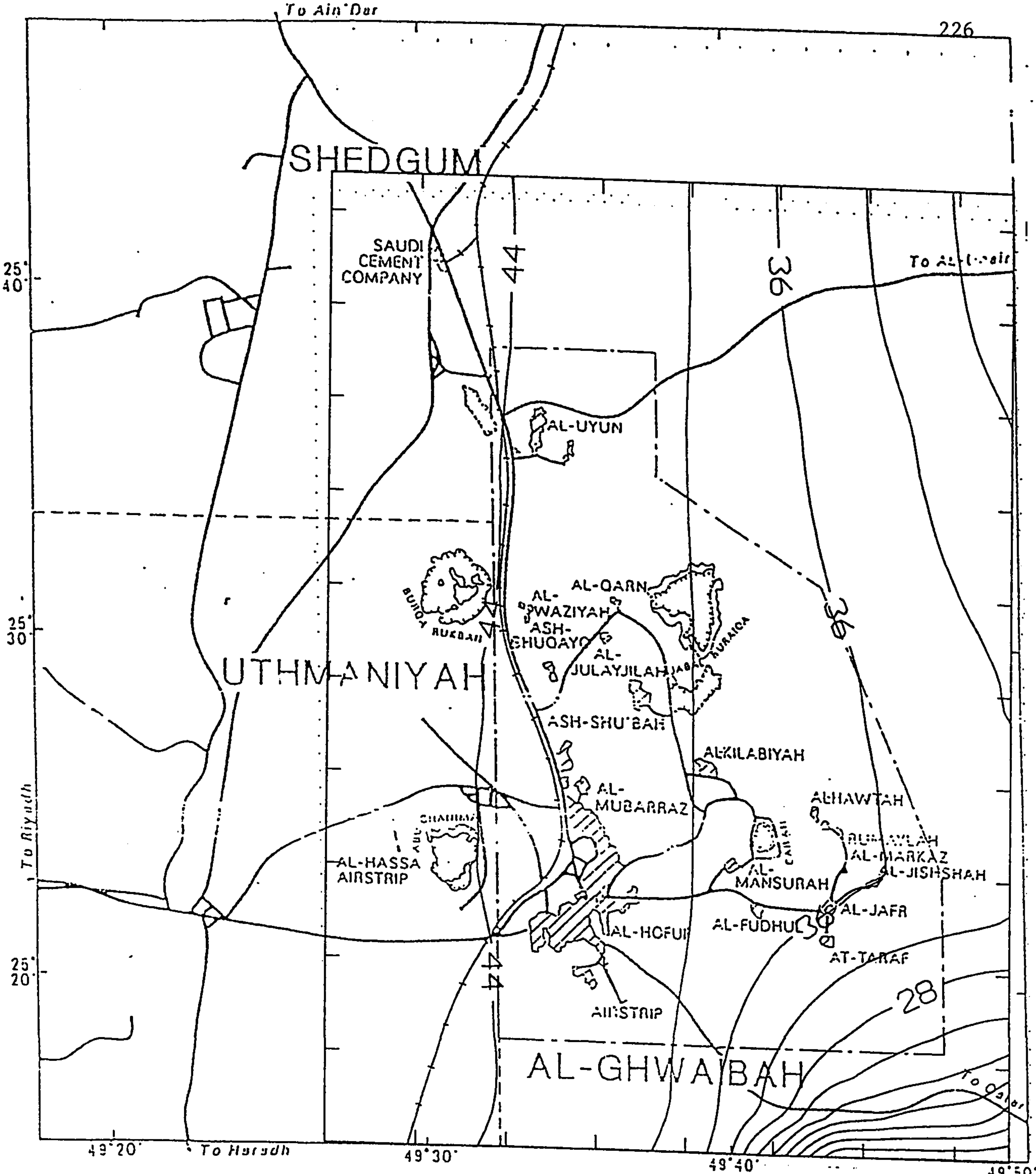


Figure A44 Simulated Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1991/1992

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

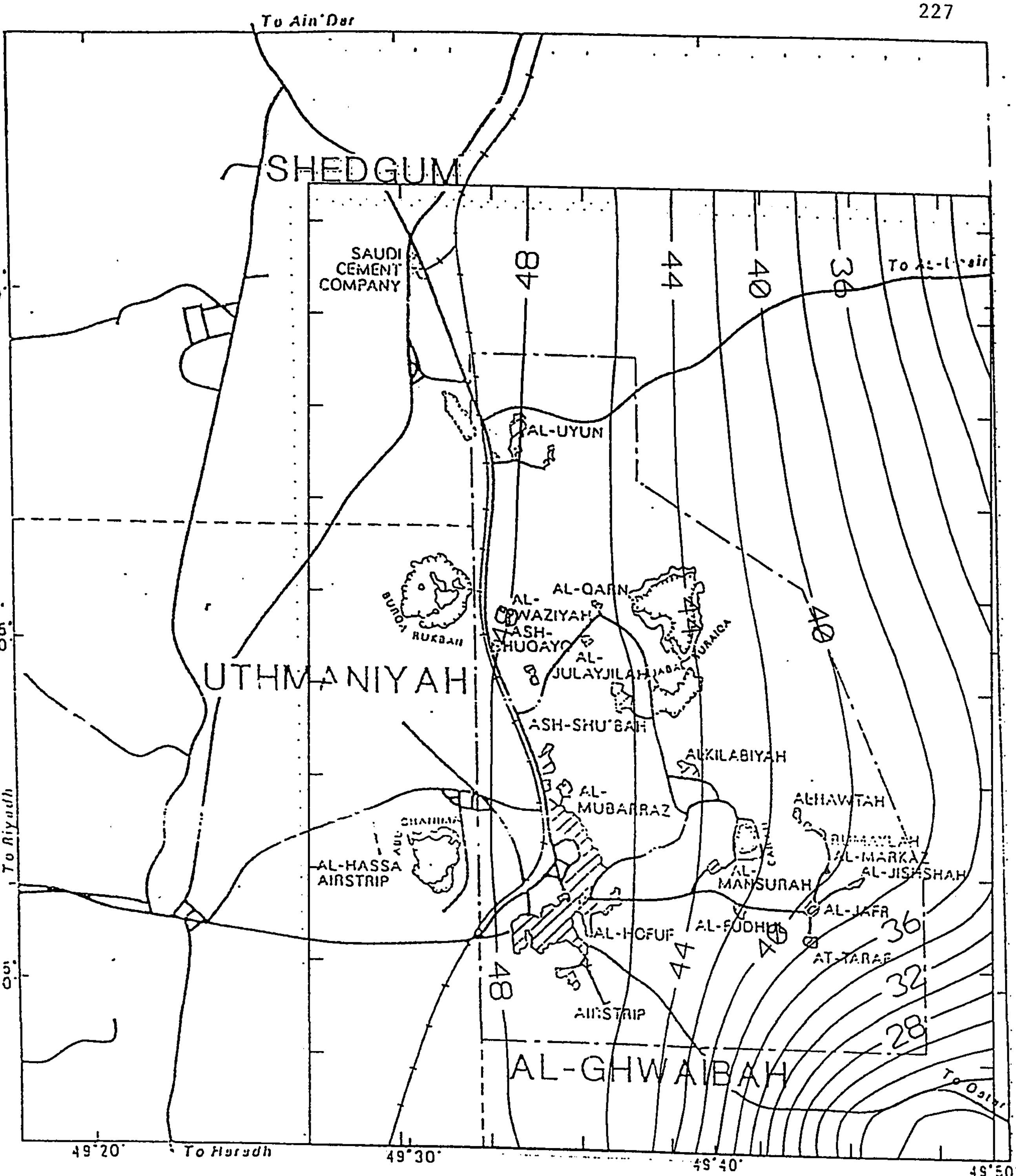


Figure A45 Predicted Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1992/1993

3 0 3 6 9 12
KM

EXPLANATION
- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

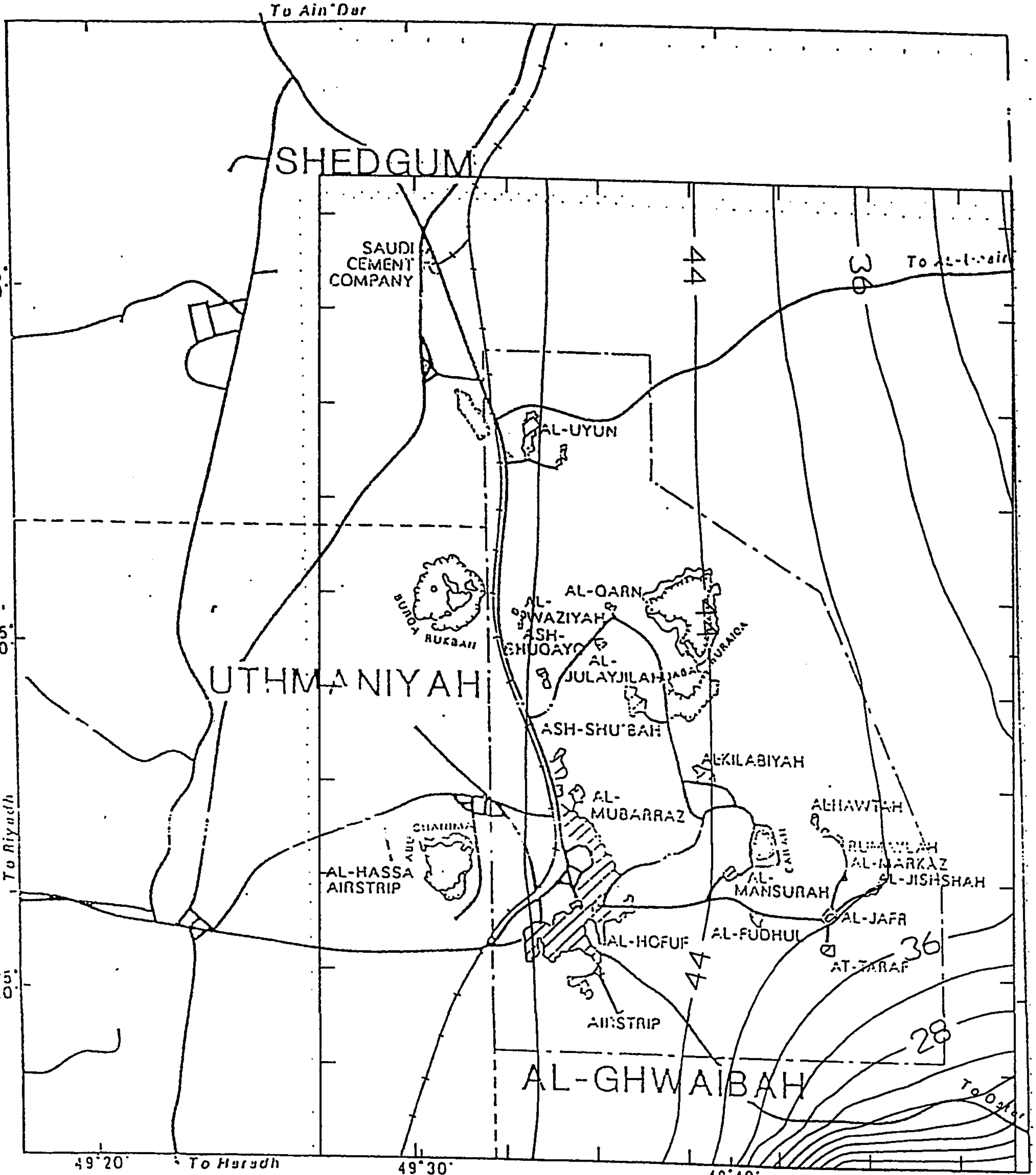


Figure A46 Predicted Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1992/1993

3 0 3 6 9 12

KM

EXPLANATION

LIMITS OF AL-HASSA OASIS
BOUNDARIES BETWEEN STUDY AREAS
MAIN ROAD
RAILROAD
TOWN OR VILLAGE
JABAL
BOUNDARIES OF THE MODELED AREA

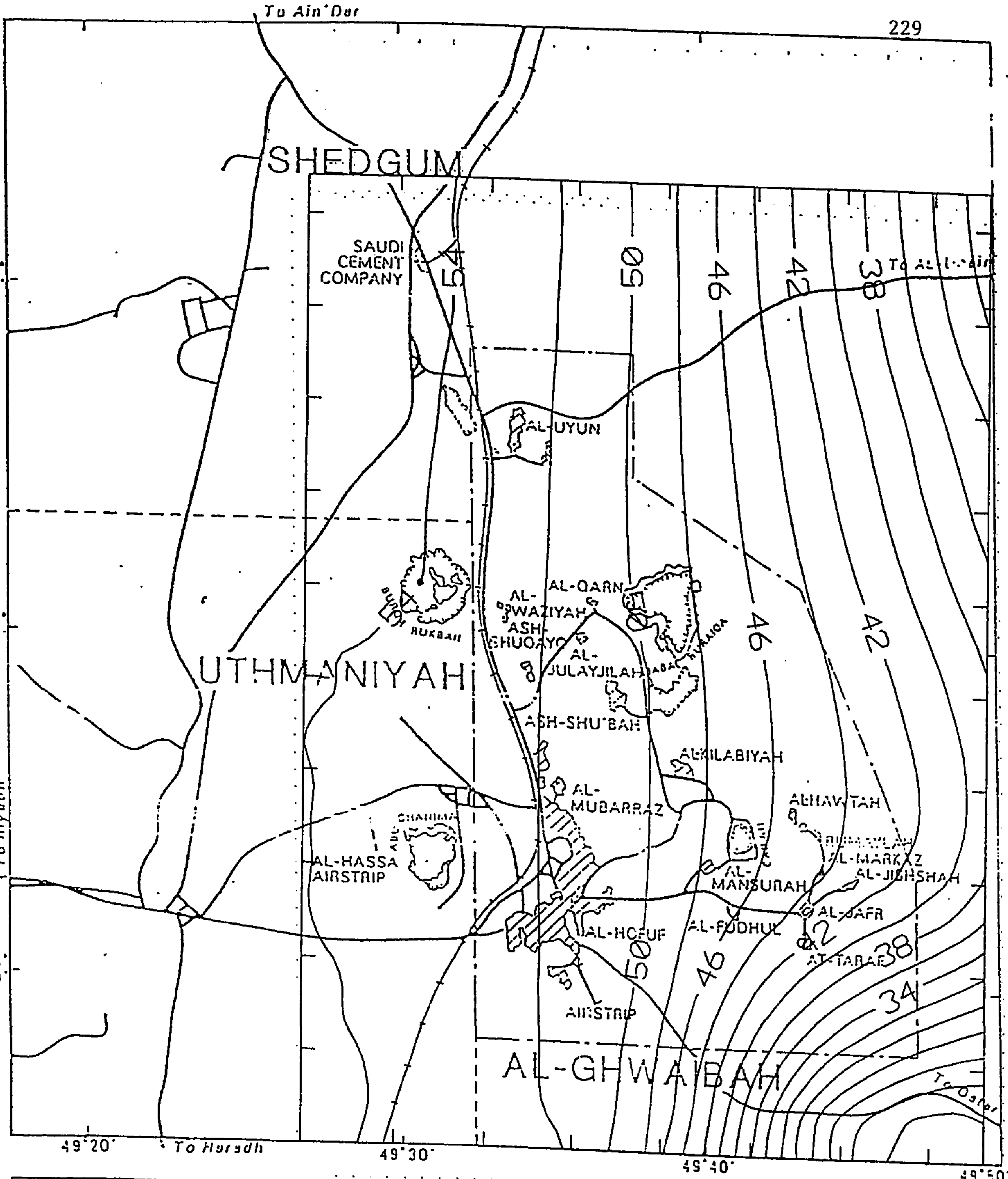
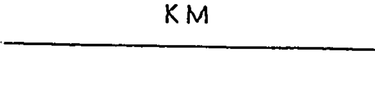


Figure A47 Predicted Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1993/1994



EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

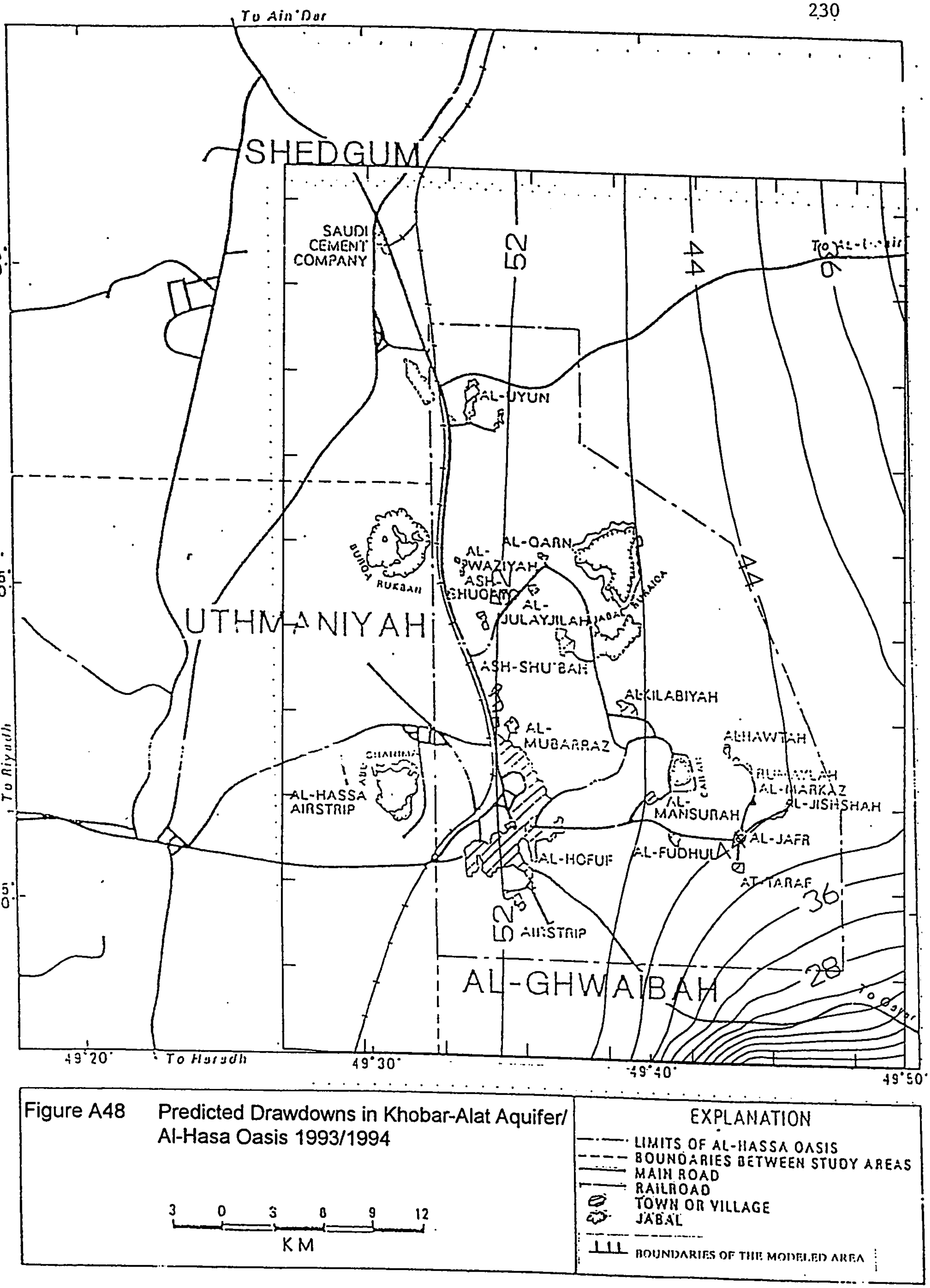


Figure A48 Predicted Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1993/1994

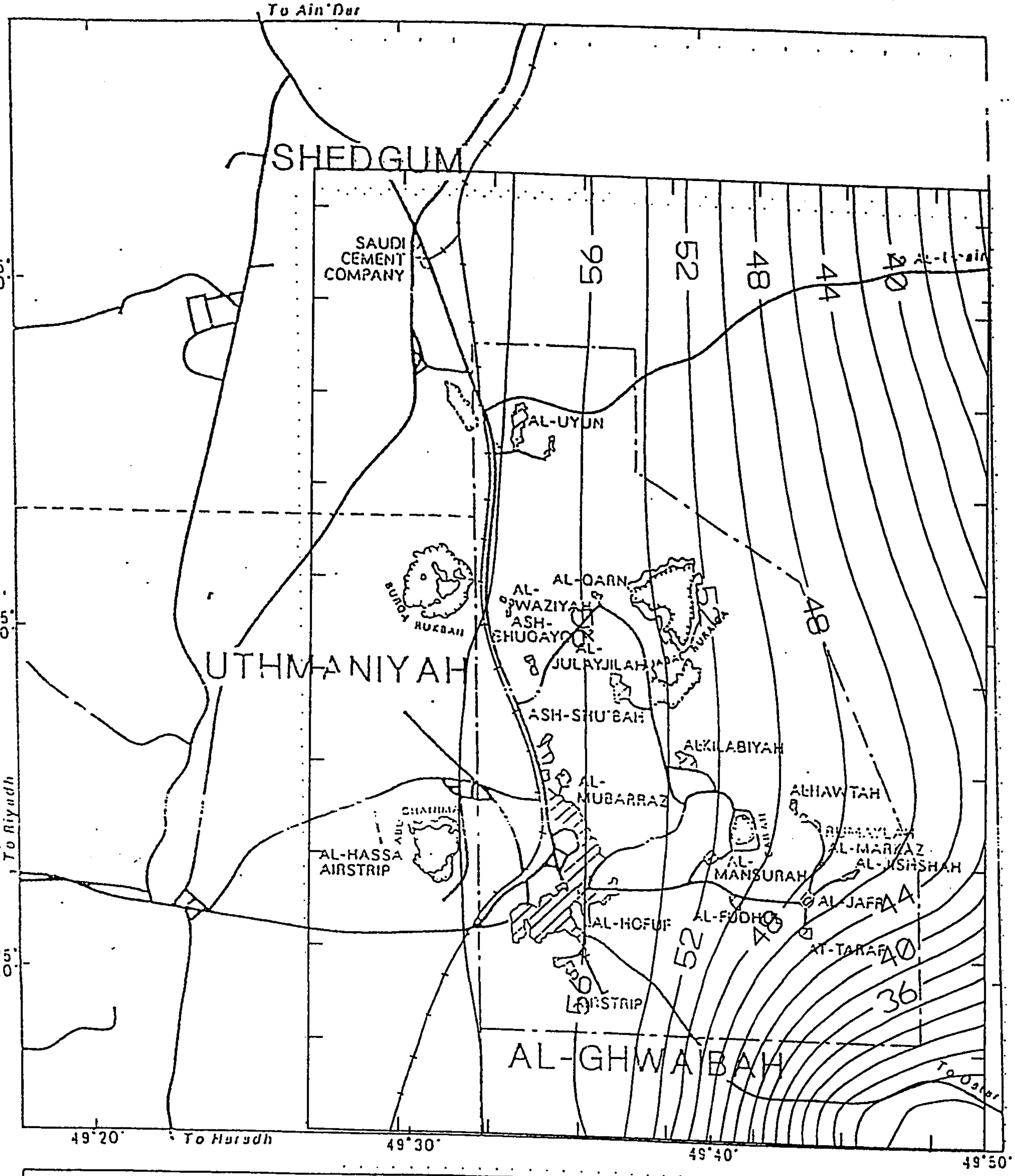


Figure A49 Predicted Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1994/1995

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

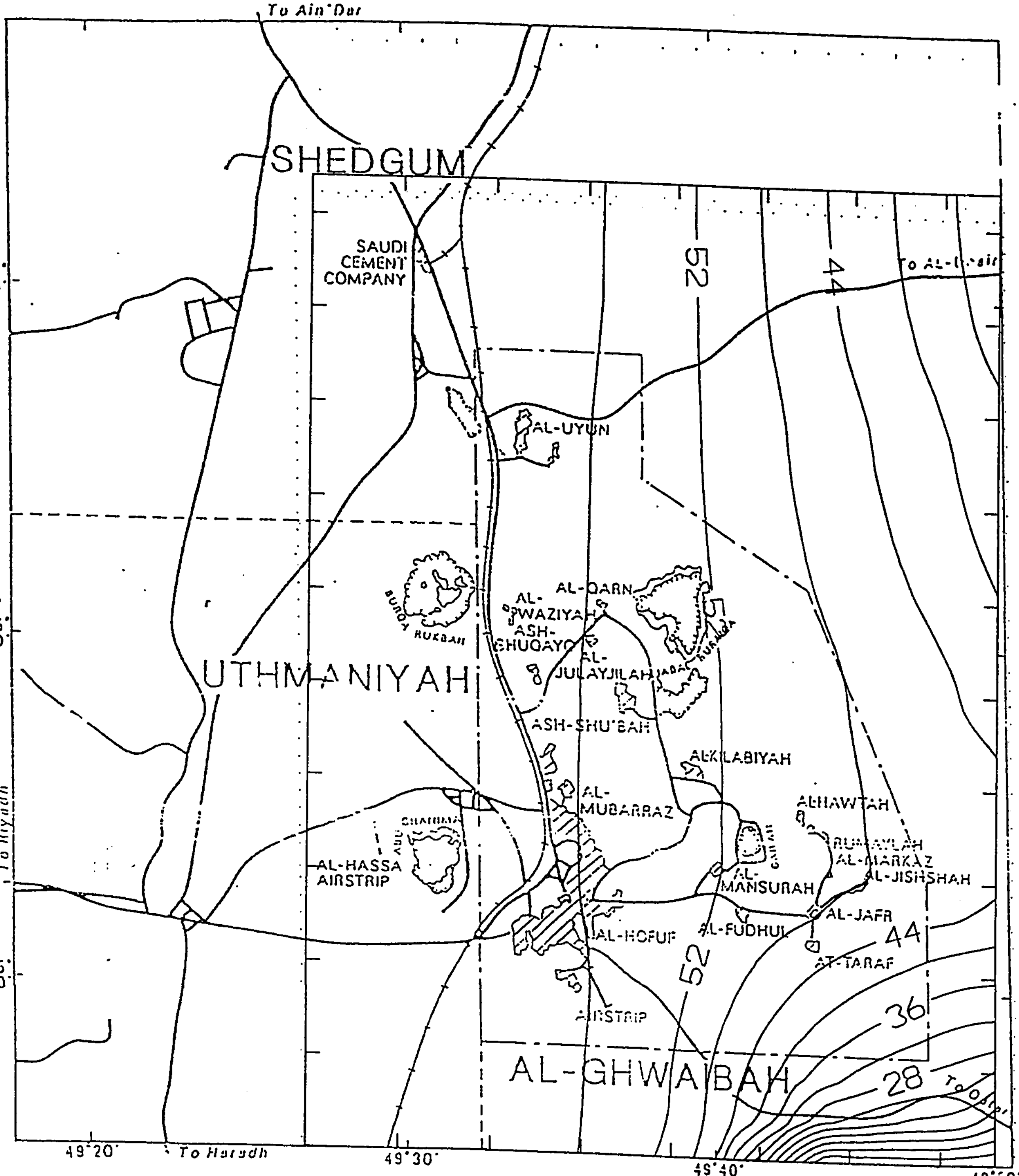


Figure A50 Predicted Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1994/1995

3 0 3 6 9 12
KM

EXPLANATION

- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA

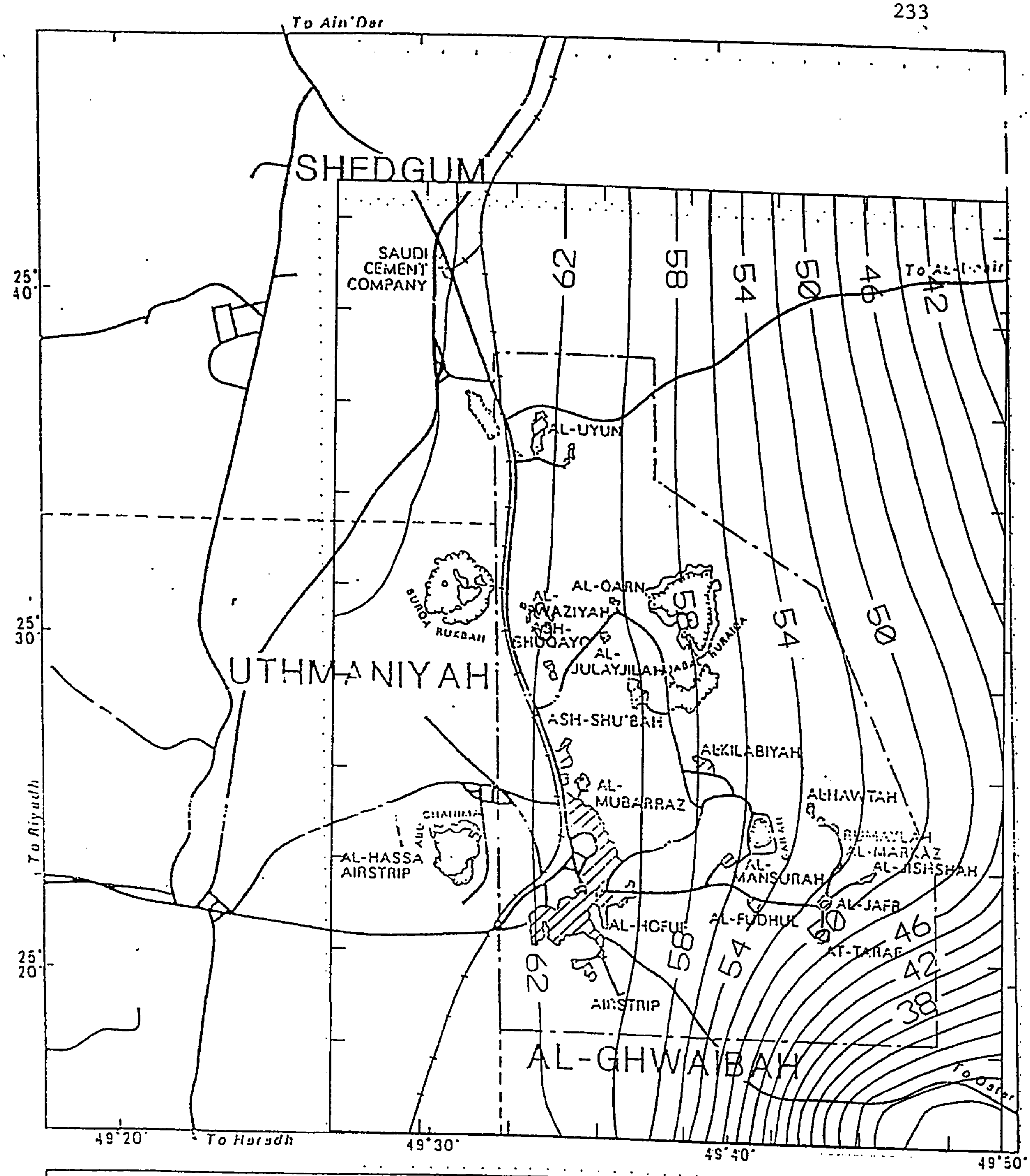


Figure A51 Predicted Drawdowns in Neogene Aquifer/ Al-Hasa Oasis 1995/1996

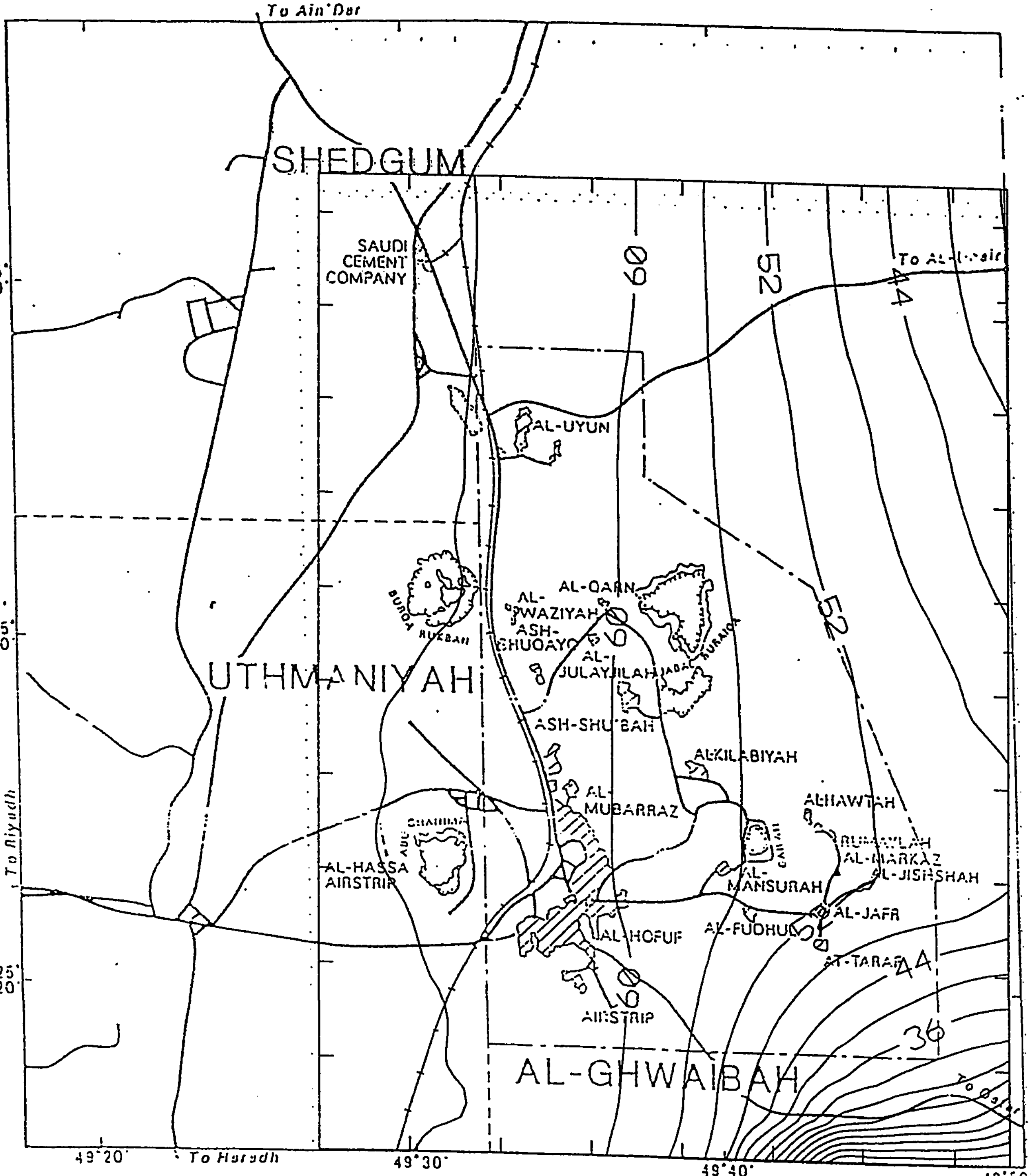
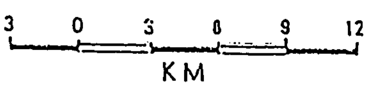


Figure A52 Predicted Drawdowns in Khobar-Alat Aquifer/ Al-Hasa Oasis 1995/1996



EXPLANATION
- LIMITS OF AL-HASSA OASIS
- BOUNDARIES BETWEEN STUDY AREAS
- MAIN ROAD
- RAILROAD
- TOWN OR VILLAGE
- JABAL
- BOUNDARIES OF THE MODELED AREA